K-Ar RELATIONSHIPS IN DOLERITE DIKES OF GEORGIA

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K-Ar RELATIONSHIPS IN DOLERITE DIKES OF GEORGIA

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SUMMARY

Twenty dolerite dikes and one sill were analysed by the conventional K-Ar dating technique to refine the timing of continental rifting of Pangaea. A range in apparent ages of 186 ± 4 m.y. to 1,659 ± 32 m.y. was obtained for doleritic whole-rock samples which is not consistent with the geologic age range suggested in the literature (160 m.y. to 230 m.y.) for the dolerites in eastern North America. One-half of the analysed samples produced K-Ar apparent ages greater than this acceptable geologic age range. These samples (with anomalously old ages) are suggested to be contaminated with environmental excess ^{40}Ar, which was incorporated in the dolerite samples upon crystallization and cooling. Much of this argon was dissolved within the minerals during crystallization. A significant fraction of this argon is proposed to reside in intergranular spaces of the contaminated dolerite samples, where the argon atoms became trapped between mineral grains or somehow diffused into those positions upon cooling. The contamination with environmental excess ^{40}Ar prohibits the calculation of valid K-Ar ages, hence these samples cannot be used to further refine the rifting of Pangaea. Nine analysed dolerite samples yielded K-Ar apparent ages which are reasonable with the requirements of age constraints. These provisionally accepted ages range from 186 ± 4 m.y. to 228 ± 5 m.y.; the

following tectonic interpretation can be made. Magmatic activity occurred in Georgia as early as 228 m.y. ago with the intrusion of some of the dolerites observed in the Georgia Piedmont. A period of quiesence occurred (10 m.y. long) followed by a second period of magmatic activity about 200 m.y. ago. Another period of quiesence occurred (10-15 m.y. long) and was followed by a third period of magmatic activity about 180 m.y. ago. Certain K-Ar and paleomagnetic data suggest that magmatic activity continued in the area until as late as 160 m.y. ago. In view of the problem of environmental excess ^{40}Ar contamination, it is possible that all the samples may contain small amounts of environmental excess ^{40}Ar. If this is the case, then no interpretation of the tectonic events can be made from these data. Olivine and quartz tholeiites fall into similar age groups, thus no correlation of chemistry with K-Ar apparent age can be suggested.

CHAPTER I

GEOLOGIC AGE AND GEOCHEMISTRY OF THE EASTERN NORTH AMERICAN DOLERITES

This paper will be concerned with the geologic age, radiometric age, and geochemistry of the dolerites in Georgia. The system of dolerite (diabase) dikes in Georgia is part of the system of dolerite dikes in eastern North America. Constraints on the age which can be derived from previous research on dolerite dikes in other parts of eastern North America can be used to establish approximate age limits for intrusion of the dolerite dikes. Stratigraphic and structural relationships of the dolerites and the rocks which they intrude can be used to construct approximate upper and lower age limits of intrusion. The constraints imposed by stratigraphic and structural relationships can be used to help determine the accuracy of radiometric and paleomagnetic geochronology.

Stratigraphic and Structural Considerations

The Triassic Association

A large number of dolerite (diabase) dikes intrude the old, metamorphosed roots of the Appalachian mountain system, which are presently the Piedmont and Blue Ridge Provinces of Georgia. Figure 1 shows the distribution of the dikes in

Georgia (Lester and Allen, 1950). The northwest striking, steeply dipping, tholeiite-olivine tholeiite dikes in Georgia (Weigand and Ragland, 1970) are a small part of a large system of dikes which occur along the full length of the deeply eroded Appalachian Mountain system from Alabama to Nova Scotia (Cohee, 1962; King, 1960; and Stockwell, 1969). Figure 2 shows the distribution of dolerite dikes and sills in eastern North America. King noted that the dikes are associated with mafic sills and flows which were injected into and effused out of a series of northeast trending grabens commonly referred to as the Triassic basins of eastern North America. King also noted that the strike of the dikes systematically changes from northwest to northeast from the southern to northern portion, respectively, of eastern North America. The dikes transect the regional trend in the southern Piedmont but are parallel to the regional trend and are more restricted to the Triassic basins in the northeast. Boreholes in the Coastal Plain of South Carolina, Georgia and Florida have shown that Triassic basins and associated igneous rocks occur under the Coastal Plain sediments of these states (Milton & Hurst, 1965; Marine & Siple, 1974; Milton & Grasty, 1969).

King (1960) commented that the dikes and graben structures probably reflected deep-seated tensile stress in the lower crust during Triassic time. King suggested that almost all of the dikes are of the simple type, that is, only one

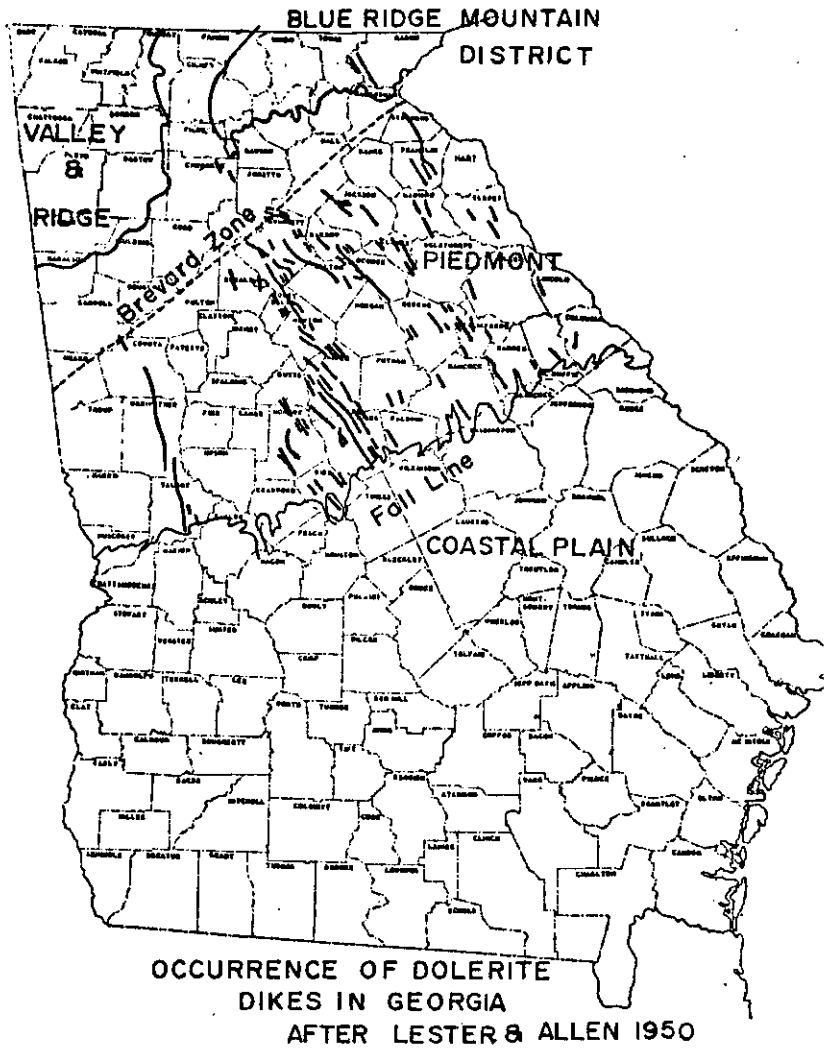
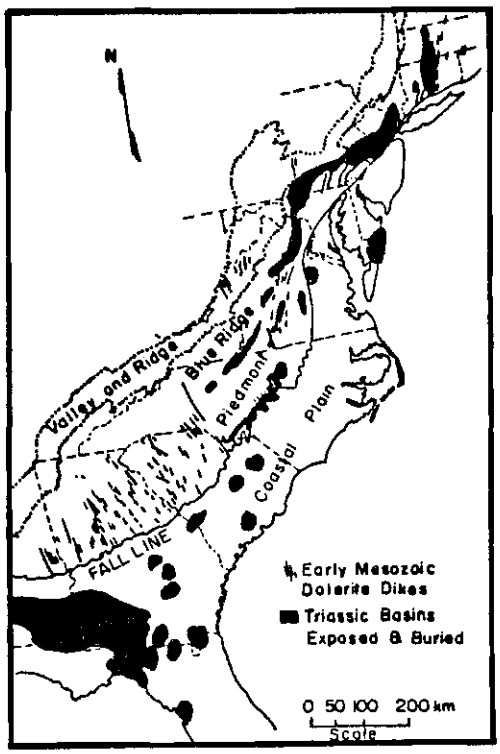


Figure 1. Occurrence of Dolerite Dikes in Georgia.



OCCURRENCE OF DOLERITE DIKES AND SILLS IN EASTERN NORTH AMERICA

MODIFIED FROM KING (1960), COHEE (1962), MILTON & HURST (1965), and MARINE & SIPLE (1974)

Figure 2. Occurrence of Dolerite Dikes in Eastern North America.

period of injection into a tensional fracture. He felt that this is geologic evidence for their contemporaneous intrusion.

The complete system of dikes in eastern North America can be further correlated with an even larger system of dikes, encompassing many dikes which occur in northeastern South America and northwestern Africa. Figure 3 shows the distribution of Mesozoic dolerite dikes in a reconstructed model of North America, South America, and Africa during the Early Mesozoic. The entire system of dikes produces a radial pattern within an elliptical area when the continents are reconstructed to their pre-rifted positions (May, 1971). May analyzed the stress pattern which might have produced such a radial pattern of dikes and concluded that the dikes were produced by a general passive infilling of tensional cracks with basaltic magma (tholeiitic-olivine tholeiitic) seeking its own density equilibration in an updoming event. The tensional cracks, which are products of such a stress distribution, are compatible with extension (upwarping) in the crust (Megrue, Norton, and Strangway, 1972). Similar upwarping was suggested to have resulted in graben formation and crustal extension which produced crustal thinning (Ross and Schlee, 1973) and to have been caused by thermal expansion due to the episodic, thermally convective, activation of a hot spot or mantle plume in the Red Sea area. Burke and Dewey (1973) have correlated such convective mantle plumes with the forma-

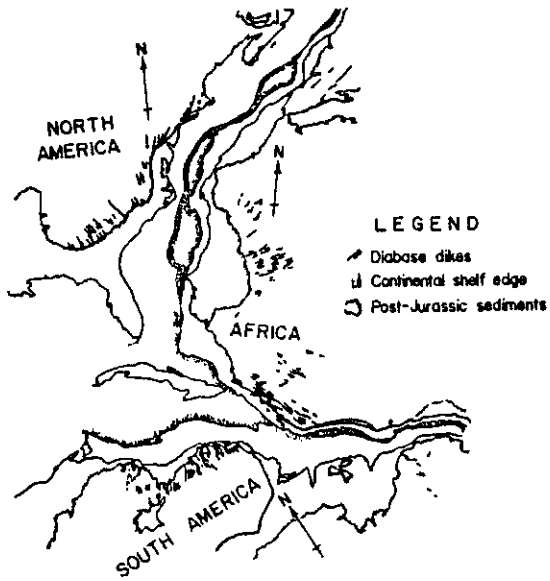


Figure 3. Occurrence of Dolerite Dikes in Eastern North America, West Africa, and Northeastern South America with the Continents Restored to their Pre-Rift Position. (After May, 1971). Present day positions of north for each continent is plotted.

tion of triple junctions (or three-armed rifts where all three arms have not been activated) presently developing where continental crust is over a plume or plumes. Anderson (1975) suggested that chemical plumes are rooted in the lower mantle and may be responsible for crustal upwarping. The Afar Region in eastern Africa is one example of a place where this process is occurring today, and will be used in this thesis in an analogy with the old triple junctions which separated Pangaea into Laurasia and Gondwanaland. The style of deformation in the Afar Region is similar to that which occurred in the old rift zones in eastern North America in Early Mesozoic time. The duration of magmatism at the Afar will suggest minimum constraints on the length of magmatic activity in continental rocks affected by other triple junctions (or rift zones) of the same type, since magmatism has not yet ceased in the Afar Region.

Dietz and Holden (1970) suggested a relative sequence of continental separations for the worldwide breakup of Pangaea. They suggest that rifting of Laurasia from Gondwanaland occurred approximately 230-160 m.y. ago(?). This rifting separated North America from South America and Africa. The supercontinent, Gondwanaland is thought to have undergone rifting during Early Cretaceous time with the separation of South America from Africa. Finally, Europe, Greenland, and North America underwent separation during Early Tertiary time. It is the initial separation of Laurasia from Gondwana-

land which is important for this study. The dolerites in Georgia were intruded during this beginning stage of breakup of Pangaea.

Age Limits (for the System)

Upper and lower age constraints can be developed on the basis of stratigraphic and structural relationships. Such limits offer an independent check on the accuracy of K-Ar geochronology. The upper age limit is based on structural considerations and the lower age limit is based on stratigraphic evidence.

Lower Limit. An absolute minimum time for intrusion of the dolerites is given by the overlap by Upper Cretaceous sediments of the Coastal Plain. A minimum time since the subsidence of continental rifting would be given by the age of the oldest sediments in the Atlantic Ocean. Ewing et al. (1966) found that a turbidite sequence of Upper Cretaceous age forms an interface for seismic reflections and is located above the salt layer referred to as Horizon A, which is considered to be Middle Cretaceous in age. Horizon A would not be the same age in all areas along the Atlantic continental margins because different rift arms of developing triple junctions probably activated at different times and different rates of sea-floor spreading, occurred at different segments of the Mid-Atlantic Ridge. The oldest segment of Horizon A should correspond to the separation of the Laurasian supercontinent from Gondwanaland. Pautot and LePichon (1970) have

shown that the salt layer in the Grand Banks is either Jurassic or Triassic in age. Diapiric structures of Jurassic age have also been mapped seismically along the continental rise near the Canary Islands and Cape Verde Islands (Schneider et al., 1969). Similar ages have been suggested for diapirs in the Gulf of Mexico. The Keathley Sequence is a magnetic quiet zone in the continental shelf of eastern North America. It has been dated with paleomagnetic data by Schmitt (1975) to be 151 m.y.

Upper Age Limit. Since radial dike intrusion and graben formation have been associated with a tensional tectonic regime resulting from the activation of mantle plumes and subsequent formation of rift zones (which later became triple junctions), structural considerations can be used to place an upper age limit on the system of dolerites in eastern North America.

The fact that the dolerite dikes in Georgia are unmetamorphosed and were intruded in a tensional tectonic environment puts them later in time than the compressive forces which formed the Appalachian mountain system. The exact end of the Appalachian orogeny is not pinned down accurately however. A series of acidic plutons, which were emplaced in what is now the Appalachian Piedmont during the waning stages or final episode of the Appalachian orogeny, were dated by Fullagar (1971) using the Rb-Sr whole rock dating method. He showed that the youngest plutons which intrude the south-

eastern Piedmont have isochron ages near 300 m.y. The Stone Mountain pluton has also been dated by Whitney et al. (1976) who produced a Rb-Sr isochron age of 291 m.y. Thus, it appears that the waning phase of the Appalachian orogeny was completed by approximately 290 m.y. ago and this must be an absolute maximum limit on the age of the dolerite dikes which intrude the youngest intrusive rocks associated with the Appalachian orogeny.

Long, Kulp, & Eckelmann (1959) dated micas from metamorphic rocks of the Georgia Piedmont with the conventional K-Ar method and determined that the last period in which the K-Ar system was disturbed occurred between 310 to 230 m.y. ago. The K-Ar apparent ages presumably represent uplift and cooling of the crystalline mountain roots. Gilluly, Waters and Woodford (1975) place the end of the Appalachian orogeny at the end of the Paleozoic. The youngest Paleozoic sediments in the Appalachian region are Lower Permian rocks of the Appalachian Plateau. These rocks have been gently folded by the compressive forces of the Appalachian orogeny. Webb and McDougall (1967) proposed an age of 235 m.y. as the boundary between the Permian and Triassic periods. Thus, on the basis of geologic evidence and the application of two independent geochronologic methods, a maximum age for the intrusion of dolerites in eastern North America can be placed in the Early Permian. The compressive forces of the Appalachian orogeny probably ceased by the end of the Permian. Thus

the end of the Permian (235 m.y.) is used as an estimated time limit for the intrusion of the dolerites in Georgia and the rest of the southeastern United States.

Geologic History of Triassic Basins

Some of the dolerite dikes of eastern North America intrude the sediments of the Triassic basins and are associated with sills and flows in the basins. The Middle Triassic index fossil Cyzicus "Estheria", is found in the Newark basin (Reeside et al., 1957). Crosscutting relationships have shown that the dikes in the basins are associated with the Mid-Triassic red bed sediments. The history of the basins is important in discerning the time of intrusive events which occurred within the basins.

Bird and Dewey (1970) suggested that the basins resulted exclusively from the tensional phase which was proposed to have occurred during the beginning stages of the opening of the Atlantic Ocean. Sanders (1971) feels that the history of the basins involves more than just a single tensional phase. Sanders proposed that he can discern five distinct phases of events within the Triassic basins. The basins have been downwarped and filled with sediments and intruded with dolerites; tilted, transected, and offset by normal faults with a second phase of magmatism; and folded in three phases whose axial trends are parallel, perpendicular and diagonal to marginal faulting. Two sets of dikes are suggested by Sanders to be post-depositional and possibly a

third set of dikes may be post-depositional. Sanders equates these three intrusive events with the three folding events that he sees, with dikes intruding perpendicular to the fold axes of each event. It should be further noted that Sanders, along with King (1967) and DeBoer (1967) view the basins as grabens, such as those that Ross and Schlee (1973) propose in their tectonic history of the Afar triple junction.

Alternatively, Faill (1973) proposes that the Newark-Gettysburg basin was a simple downwarped basin, due to crustal extension and thinning, and was filled with sediments before faulting began. In a later event he proposes that the basin was tilted north and northwestward with concomitant folding and faulting. Finally dikes and sills intruded in three phases before deposition ended according to Faill. Faill suggests that the geologic evidence shows that a continuous system of faulting does not occur on the north and northwest margins of the basins, which would be required if the basins were true grabens. Syndepositional faulting would also be required if the basins were grabens, and Faill does not feel that the geologic evidence shows such faulting. Faill suggests that true graben systems such as the East African and Rhine systems have a wide range in composition of the associated igneous activity. Faill notes that the limited tholeiitic-olivine tholeiitic composition of igneous activity in the basins of eastern North America does not compare with the wide variation in chemistry of the magmatism

in true grabens. Furthermore, Faill suggests that the North American Triassic basins are mimetic of Appalachian structure and do not cut across regional structures as do true grabens such as the East African and Rhine graben systems. Faill compares the basin formation of North America with the type that initially occurred in the Baikal rift, which had a nascent downwarping and basin filling stage, accompanied by basaltic vulcanism prior to rifting, although the igneous activity continued during the graben development of the Baikal rift whereas in eastern North America the magmatic activity was interrupted. The basaltic activity associated with the Baikal rift is limited to tholeiitic and trachybasaltic composition.

At present rifting systems, the grabens are the locus of crustal separation where new crust is injected as dike intrusions parallel to the long axis of the rift. Faill notes that the separation of Laurasia from Gondwanaland occurred to the east of the location of the Triassic basins of North America. Thus, it appears to Faill, that the formation of the Newark-Gettysburg basin was interrupted before it became a true graben by a relaxing of extensional stresses (as a result of the uplift of the southern Piedmont or subsidence of its flanks) and the associated folding and rotation of the Triassic basins. The Triassic basins are proposed by Faill to be movements in the pre-existing orogenic belt lying next to a major rift which was responsible for the

separation of Laurasia from Gondwanaland.

The dikes have been observed by King (1967) to cut across regional trends hundreds of kilometers from the basins into old crystalline metamorphosed mountain roots of the Piedmont of eastern North America. Faill does not consider the dikes as they occur outside the basins in the development of his tectonic model. Sanders' interpretation of the Triassic basins provides a place in the tectonic history for the dikes which intrude rocks outside the basins. Sanders places stages of dike intrusion during the episodes of folding of the basins. The arching of the Piedmont, as suggested by Faill, could be responsible for crustal extension in the Piedmont and the intrusion of dolerites into the southern Piedmont.

DeBoer (1967) offered an earlier view of the sequence of events involving the sills, flows, and dikes of the Triassic basins. DeBoer envisioned five sequences of events concerning the development of the Triassic basins and associated igneous activity. The first period was one of graben subsidence along pre-existing lines of weakness in the NE-SW direction and one of deposition of clastics syntectonically during the mid-Triassic, with an accompanying period of igneous activity. The Palisades sill formed during this period. DeBoer used paleomagnetic data to show that the sedimentary beds were essentially horizontal at the time of igneous activity. DeBoer's second phase began with longitudinal arch-

ing in the centers of the grabens which was almost parallel to the old Appalachian axis. This caused uplifting and tilting of the grabens. The third phase consisted of another period of graben subsidence and of longitudinal folding of the basins' sediments. If an associated period of sedimentation occurred in DeBoer's third phase, the sediment has not been preserved in the stratigraphic record. DeBoer associated a fourth period with increased tectonic activity causing strike-slip faulting along older lineaments and transverse or cross-folding of the sediments in the basins. The fourth period ended with the development of tensional fractures which were intruded by mafic magmas. Thus, DeBoer suggested two periods of igneous activity separated by additional periods of deformation in Early Mesozoic time. DeBoer (1968) considered the White Mountain Complex (gabbroic in composition) (125-135 m.y. old) and the Monteregian gabbros (124 m.y. old) to be associated with the fifth and final period of tectonic and magmatic activity in eastern North America. This fifth period is considered to be local and has not been suggested by other researchers to be associated with the intrusion of Early Mesozoic dikes and sills.

The existence of dikes several hundred kilometers from the basins and their apparent common origin suggest that a larger area than that occupied by the basins was affected by continental rifting. The timing of events in the basins may be different from the geochronology of the dikes intruding

the southern Piedmont. It is also possible that some dikes in the southern Piedmont are synchronous with events in the Triassic basins in Eastern North America. Upwarping certainly occurred over a larger area than that which is occupied by the grabens or basins.

K-Ar and paleomagnetic geochronology can be used to help establish the time of intrusion and crystallization of dolerites in eastern North America. This has been done for several segments of the dolerite system of eastern North America, northwestern Africa and northeastern South America. These data are important in developing a unified picture of dolerite intrusion in eastern North America and in Georgia.

Radiometric Geochronology

Eastern North America

One of the most thoroughly studied dolerite bodies in eastern North America is the Palisades sill. Erickson and Kulp (1961) dated the Palisades sill with the conventional K-Ar method. They used a sample of dolerite, a biotite from the country rock near the contact and a hornfels at the base of the sill. Those dates are 202 $\pm$ 10 m.y., 190 $\pm$ 5 m.y. and 193 $\pm$ 4 m.y. respectively. Armstrong and Besancon (1970) also dated the Palisades sill and got an age of 192 $\pm$ 4 m.y. using K-Ar geochronology. Dallmeyer (1975) provided $^{40}Ar/^{39}Ar$ incremental release spectra for the Palisades sill and produced total gas ages of 192 $\pm$ 9 m.y. and 193 $\pm$ 9 m.y. These

ages are in accordance with the earlier results, but Dallmeyer also used palynologic studies done in the Hartford basin, which has stratigraphic correlatives with the Newark basin, to further suggest an earliest Jurassic age for magmatism in the basins.

The most extensive study done on eastern North American dolerites with K-Ar geochronology is that of Armstrong and Besancon (1970). They sampled dolerite dikes from North Carolina through Connecticut. Two distinct groups of K-Ar ages were found, the older one ranging from about 225-230 m.y. and the younger one from about 190-200 m.y. The older dates were interpreted by Armstrong and Besancon to be reflective of the true age of intrusion. They cited a zeolite facies "burial" metamorphism of the Newark group sediments as a possible reason for many of the younger ages, which would be cases of Ar loss. Thus a definite Triassic time of intrusion (approximately 225 m.y.) was suggested by Armstrong and Besancon to be the actual time of emplacement of dikes and sills in eastern North America. The minerals, pumpellyite and prehnite, have been found in many of the dikes which intrude the Piedmont from North Carolina to Maryland (Weigand and Ragland, 1970). Armstrong and Besancon also found a couple of very old K-Ar dates for dikes which contained less than 0.1% K by weight and suggested that these dikes contained excess ^{40}Ar. A few of the younger dates obtained by Armstrong and Besancon were from rocks which had

no secondary alteration, and thus they may represent true ages.

Carmichael and Palmer (1968) provided K-Ar dates and paleomagnetic poles of the North Mountain basalts of Nova Scotia. They obtained K-Ar dates of 217 m.y. for the upper lavas of the North Mountain and 178, 196, and 204 m.y. for the lower lavas of the North Mountain area. Larochelle and Wanless (1966) dated the large Shelburne dike in Nova Scotia, obtaining a date of 197 m.y. This is the only dolerite dike in Nova Scotia.

K-Ar ages were determined for four dolerite dikes in Rockingham County, Virginia, by Wampler and Dooley (1975). The apparent K-Ar ages range from 175 $\pm$ 5 m.y. to 200 $\pm$ 7 m.y. It should be noted that these dikes were intruded in the Ridge and Valley province and were probably not affected by the zeolite facies "burial" metamorphism present in the Newark group sediments. This was confirmed by inspection of thin-sections.

Neathery *et al.* (1975) dated two dolerite dikes which intrude the crystalline Piedmont of Alabama. Their results were ages of 161 $\pm$ 4 m.y. for a quartz normative tholeiite and 193 $\pm$ 5 m.y. for an olivine normative tholeiite. They suggested that the more basic olivine normative tholeiites were generally older than the more differentiated quartz normative tholeiites.

The published K-Ar data on the dolerite dikes and

sills in eastern North America show a total range of 161 to 230 m.y. (excluding a few anomalously high dates), an approximate time span of 70 m.y. These data are consistent with the upper and lower limits established above for the time of emplacement of the dolerites, and suggest that continental rifting occurred during the Triassic and Jurassic periods over a time span of about 70 m.y. Different magmatic events are thought to have occurred within this time span. Additional K-Ar dates from other continents involved in the rifting of Laurasia from Gondwanaland as well as evidence from other geochronologic methods must be sought to further refine the timing of rifting. Also, by looking at the K-Ar dating of dike intrusions at present day triple junctions, insight into the timing of continental rifting and intrusion of dikes and sills might be found.

Northwest Africa. The most significant and definitive work pertaining to K-Ar geochronology on dolerite dikes in Africa, has been recently done by Dalrymple, Gromme, and White (1975) on Liberian dolerite dikes. The Liberian dolerite dikes are part of the system of dikes which were intruded during the rifting of Laurasia from Gondwanaland.

Tholeiitic diabase dikes trending northwest, parallel to the coastline, intrude the PreCambrian crystalline rocks of northwestern Liberia. The crystalline rocks have been subdivided into three provinces: The Liberian age province approximately 2,700 m.y. old, the Pan-African age province

approximately 550 m.y. old, and the Eburnean age province approximately 2,000 m.y. old. Unmetamorphosed sedimentary rocks crop out along the coast of Liberia, and are the Paynesville sandstone, the Farmington River Formation and the Edina sandstone. Dikes and sills intrude the Paleozoic Paynesville sandstone.

Dalrymple and his coworkers dated the dikes using the conventional K-Ar method and the $^{40}Ar/^{39}Ar$ method on whole rock samples and plagioclase mineral separates. The conventional K-Ar analyses produced discordant ages which ranged from 186 m.y. to 1,213 m.y. About two-thirds of the dikes gave anomalously old ages much in excess of the expected approximate 200 m.y. age proposed as the time of rifting of Laurasia from Gondwanaland.

It was noted by Dalrymple et al. that the anomalously old ages occurred in the dikes which intruded the granite gneisses of Liberian age, the metasedimentary and metaigneous rocks of Pan-African age, and the paragneisses, amphibolites, migmatites, and granitic plutons of Eburnean age. Those dikes which intruded the Paleozoic unmetamorphosed sandstones along the Liberian coast produced K-Ar plagioclase mineral ages of 178 $\pm$ 4 m.y. to 192 $\pm$ 6 m.y., which is in accordance with the age range established for the eastern North American dolerites.

In the $^{40}Ar/^{39}Ar$ study three of the samples produced disturbed incremental release spectra, that is, an irregular

pattern of $^{40}Ar/^{39}Ar$ ratios. These samples were from the metamorphic provinces in Liberia and had anomalously old K-Ar conventional ages. Two of the neutron-irradiated samples produced broad plateaus in the incremental-release diagrams at a $^{40}Ar/^{39}Ar$ ratio equivalent to 185 m.y. These two samples were collected from dikes which intrude the Paleozoic sandstones along the Liberian coast.

Dalrymple and coworkers concluded that excess ^{40}Ar has been incorporated in the dikes with anomalously old ages and those which produce disturbed $^{40}Ar/^{39}Ar$ incremental release spectra.

Briden et al. (1971) studied the Freetown complex in Sierra Leone, Africa with paleomagnetic and K-Ar geochronology. They obtained K-Ar dates of 165 m.y., 172 m.y., and 194 m.y. These ages are reasonable with respect to the ages of the Liberian dikes.

In Morocco, the Draa Valley sills were studied with paleomagnetic and K-Ar geochronology by Hailwood and Mitchell (1971). They obtained remarkable agreement in the K-Ar apparent ages of three samples; 182 m.y., 184 m.y., and 182 m.y. Furthermore, they dated the Foum-Zguid dike in Morocco and obtained four K-Ar apparent ages of 182 m.y., 182 m.y., 186 m.y., and 187 m.y. The Foum-Zguid dike is contemporaneous with the Draa Valley sill intrusion.

Northeast South America. In South America, the only K-Ar studies of Mesozoic dolerites which have been done were

by Hebeda et al. (1973). The extensive north-northwestern trending dolerite dikes in Surinam have average K-Ar apparent ages of 227 m.y. Hebeda et al. have suggested that there were many uncertainties which may have affected the K-Ar ages of the dikes in Surinam. They suggested that some of the dolerites of western Surinam may contain excess ^{40}Ar and might have also been affected by argon loss. There is also evidence that some of the dikes in Surinam might be PreCambrian. These dikes gave a range of K-Ar apparent ages of 1.2 to 2.7 b.y. and intruded basement rocks which are not older than 1.81 b.y. Work on the dolerite dikes in Guiana, and French Guiana is notably lacking in the fields of K-Ar and paleomagnetic geochronology, as far as can be ascertained.

The Afar Region. The last reference to previous work in K-Ar geochronology presented in this paper is the work of Megrue, Norton, & Strangway (1972). They studied the radial pattern of dikes which intrude the Ethopian rift zone with K-Ar geochronology and paleomagnetics. The age range produced in this study should provide a minimum estimate of the duration of magmatic activity in continental rocks at an arm of a triple junction, provided that the K-Ar ages are valid. The rifting phase of a continental mass is defined here as the activation of a hot spot reflected surficially as updoming and the formation of three (usually) rift arms. The duration of the rifting phase is considered to be the length

of time from beginning of tensional failure until axial dike emplacement is well underway at the spreading ridges in the arms of the triple junction. The tectonic regime of compression indicates the end of the tensional phase responsible for continental rifting.

The plateau regions in the Ethopian rift consist of Eocene-Oligocene alkali basalts which thicken at rift margins. Mohr (1972) finds the youngest volcanics along the central axis of the rift valley whereas the older basalts form outcrops in the plateau regions. The dikes which intrude the Afar region show a range in strike from N60W to N70E, produce a radial pattern, and are steeply dipping. The predominant N-S, N10W, and N10E striking dikes intrude subparallel to the rift valley trend. K-Ar analyses of basalt flows and dikes by Megrue et al. (1972), produced a range of apparent ages in the dikes from 3 m.y. to 66 m.y. The youngest dikes appear in the rift margins and in the plateau province. Megrue et al. found two groups of dikes on the basis of potassium content; those with less than 0.8% K by weight and those with greater than 1.25% K by weight.

Mohr (1972) studied the regional significance of vulcanism in the Afar region. K becomes more deficient rapidly toward the Red Sea rift (reflecting less differentiated basaltic material). In general, TiO_2 and SiO_2 increase from the rift to the plateau. Mohr suggested that this gradation of chemical content indicated a shallowing in the zone of

partial melting in conjunction with crustal thinning from plateau to rift. The shallow melting in the Red Sea rift produced less differentiated basaltic material. The greater the distance from the rift, according to Mohr, the thicker the crust becomes and the zone of melting becomes progressively deeper. The deepening of the zone of melting produces more alkalic (basanites) basalts. Mohr also proposed that lateral inhomogenieties in a mantle plume may give rise to more silicic magmas toward the edges of the plume.

Megrue et al. (1972) found that there is no apparent age difference between the two chemical groups they describe, but they suggest that there might be a correlation of chemistry with the distance from the rift valley margin. They suggest that the dikes have been affected by some excess ^{40}Ar. As evidence for this, they produced a diagram of K-Ar apparent age versus K content in weight percent. Their reasoning was that if there were excess ^{40}Ar in the samples the rocks with low K content would show the presence of excess argon more readily. They plotted all the dikes on the same diagram and did not find a trend. Their conclusion was that the dikes had not been affected by excess ^{40}Ar.

Megrue et al. further suggested that there might be a rotation of the stress field which produced the fractures which the dikes intruded. They produced rose diagrams of strikes for different age groups of dikes, which they interpreted as showing a change in principle stress directions

with time.

Megrue et al. suggested that the crust in the Ethiopian rift has undergone extension for more than 30 m.y. and that the rifting is not yet completed. Gass (1972) suggested that the time interval for updoming, graben formation, and dike intrusion in the Ethiopian rift area is approximately 70 m.y. The range in radiometric ages of dikes, sills and flows associated with the early rifting of Laurasia from Gondwanaland correspond to a similar time interval of 70 m.y. Is the agreement between the times fortuitous, or do they truly represent how long continental rifting requires? Paleomagnetic data provide additional information about the chronology of Early Mesozoic tectonic events, and can be used to establish relative age relationships which are independent of K-Ar data.

Several cases of discordant K-Ar apparent ages have been cited, so paleomagnetic geochronology is important in providing a check on the validity of K-Ar dates. A thorough review of the literature in this field is not the main purpose of this study, but pertinent paleomagnetic date will be presented to place further constraints on timing of continental rifting.

Geophysical Constraints

Paleomagnetic Geochronology

Eastern North America. DeBoer (1962, 1968) studied

the paleomagnetism of the Mesozoic dikes in eastern North America. Using the results of earlier workers and additional data, DeBoer found a mean paleopole for the magmatism to be located at latitude 62°N and longitude 100°E which he interpreted as an Earliest Jurassic pole. On the basis of paleomagnetic data, DeBoer (1968) suggested that four periods of volcanic activity in Connecticut could be distinguished on the basis of variations in thermoremanent magnetic inclinations. These periods extend from the Late Triassic to Early Jurassic and, in order of decreasing age are: the Talcot flows, the Holyoke flows, the Hampden flows and the Higganum flows.

DeBoer correlates vulcanism among all the Triassic basins in eastern North America. His correlations suggest that igneous activity occurred for a longer time in Connecticut and DeBoer suggests a northeastward displacement in volcanic activity in Late Triassic and Early Jurassic times. Thus, DeBoer implies that an expansion of geanticlinal arching progressively northeastward along the Appalachians occurred in Early Mesozoic times. Carmichael and Palmer (1968) produced paleopoles in the North Mountain basalts in Nova Scotia which suggest a crystallization age of 200 $\pm$ 10 m.y.

Watts prefers to use the reconstruction of the continents based on the paleopoles of Mauk, French and Van der Voo (1974) over the reconstruction used by Bullard *et al.* (1965)

and suggests that the Atlantic continents were not separated when the dolerites of the southern Appalachians acquired their magnetization upon cooling. Watts (1975) suggests a mean paleopole position for the dolerites in the southern Appalachians to be 65°N latitude and 80°E longitude with an average semi-angle cone of 95% confidence of 4.86°. This difference in paleopole from DeBoer's is based on 299 samples versus 34 samples in DeBoer's study. Furthermore, Watts used at least three cores from each location to check on the internal consistencey of magnetic directions. Watts' data suggest contemporaneous intrusion of most of the dikes in the southern Piedmont. Watts suggests an age of 170 m.y. for dolerites in Georgia. Dalrymple et al. (1975) compared reliable pole positions from eastern North America dolerites and determined an average paleopole, based on 16 samples, of 65.0°N longitude and 94.7°E longitude and a semi-angle cone of 95% confidence of 4.4°, for 170 to 200 m.y. old rocks.

Western Africa

Dalrymple et al. (1975) produced paleomagnetic data for Liberian dikes. They determined an average paleopole based on 25 samples to be at latitude 68.5°N and longitude 242.4°E with a semi-angle cone of 95% confidence of 3.6°. Dalrymple et al. suggest that the small variance among paleopoles indicates that the dikes are contemporaneous even though K-Ar data in their study produced a very large spread in apparent ages for the dikes. This further supports the

suggestion that excess ^{40}Ar was incorporated into the Liberian dikes upon crystallization and subsequent cooling.

Briden et al. (1971) produced paleopoles for dolerites in the Freetown complex in Sierra Leone, Africa. They observed that the polarity of the magnetic field changed from reversed to normal during the cooling of the Freetown complex. Thus there is some age difference between volcanic events in the dolerites of Africa.

Not much paleomagnetic data has been produced for the dikes in South America. Veldkamp et al. (1971) suggest a paleomagnetic age of 227 m.y. for dolerites in Surinam. More paleomagnetic data from South America is needed to complete the picture of continental rifting in that area.

Magnetic data can also be used in conjunction with stratigraphy to establish the age of some of the oldest sediments in the Atlantic Ocean and thus a minimum age for rifting of Laurasia from Gondwanaland. The seaward portion of the marginal quiet zone off eastern North America (Keathley Sequence) and that off northwestern Africa resulted from a dominant normal magnetic polarity prior to 150 m.y. ago and was related to initial sea floor spreading (Larson and Pitman, 1972). The quiet zone of the Keathley sequence has been interpreted as a time of normal magnetic polarity. Rapid polar movements,associated with large scale reorganization of plate motions,traces out a "hair pin" path of polar wandering (Irvin and Park, 1972). They imply that the hairpin path

corresponds to the opening of the central Atlantic Ocean. The rate and direction of continental drift after an initial rifting phase have varied since the late Triassic (Pitman et al., 1971). Initiation of rifting was not associated with an active phase of continental drift and sea floor spreading according to Pittman et al. (1971). They suggest that spreading at the rate of 4.0 cm/yr. began about 180 m.y. and continued until approximately 81 m.y. ago. The time period between 200 m.y. and 180 m.y. is suggested to be associated with slower rates of sea floor spreading and continental drift of less than 2.0 cm/yr. The spreading rate was essentially negligible 200 m.y. ago (Phillips and Forsyth, 1972).

Schmitt (1975) produced additional paleopoles on the Keathley sequence to further refine the timing of deposition of the sequence during the magnetically quiet period associated with the initial rifting phase of continents. His results place the base of the Keathley sequence at an age of 151 m.y. Thus it is possible that the central Atlantic Ocean did not begin active sea sloor spreading until as late as approximately 151 m.y. ago. This fits well with the 170 m.y. time of intrusion proposed by Watts (1975) for the dolerite dikes in Georgia.

Heat Flow Constraints

Jaeger (1957) produced a series of cooling curves for dolerite sills. Based on the assumption that a 100 meter

thick dike, initially at 1100°C intruded rock at the base of the crust at 500°C. Jaeger calculated that the sill was one-half crystalline at 800°C. Jaeger showed that a typical time for complete solidification and cooling of a dike is proportional to the square the thickness of the dike. Irvine's (1970) cooling curves allowed Smith et al. (1975) to calculate that a 2 km thick sill initially at 1100°C would be half crystallized in less than 20,000 years when intruded at the base of the crust at 500°C. Dikes with widths of 100 m or less would cool in a few hundred years according to heat flow calculations.

Any differentiation of the liquid phase of a magma must occur within the interval of crystallization. Paleomagnetic relationships might show a distinction between the intrusion of dikes and sills derived from the same magma, and thus may offer a way to show time intervals between chemical changes specifically related to magmatic differentiation.

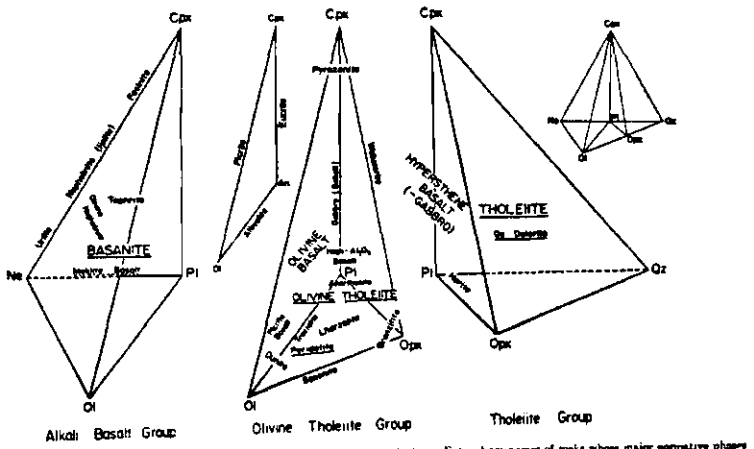
K-Ar geochronology with a 2% analytical precision at the 95% confidence level can only distinguish differences in ages of Early Masozoic dikes if they differ by more than 4 to 5 m.y. It is suggested that K-Ar geochronology cannot distinguish between the timing of intrusion of dikes or sills of the same magmatic event, which would be constrained to from within a time interval considerably less than a million years.

Geochemistry of Dolerites

Petrology

Chemically, dolerites are basalts. Petrologists divide basalts into two series; the calculkalic series (Bowen trend) and the thoeiitic (Fenner trend) series (Myiashiro, 1975). Using normative mineralogy plotted on a diopside-forsterite-nepheline-quartz tetrahedron, five chemically distinct basalt compositions can be discerned. Figure 4 shows those five groups: tholeiite with normative quartz and hypersthene; tholeiite with normative hypersthene; olivine tholeiite with normative hypersthene and olivine; olivine basalt with normative olivine; and basanite with normative olivine and nepheline. The Tholeiitic series (tholeiitic picrite basalt--tholeiitic olivine basalt--basalt--basalt--hypersthene basalt) is the type of differentiation series that the tholeiitic basalts of the Mesozoic dolerite sills, sheets, dikes and other plutons follow. These igneous bodies did not complete differentiation to produce all the rocks of the series.

The exploded view of the Di-Fo-Ne-Q tetrahedron in Figure 4 can be used to classify the dolerites in eastern North America. The olivine tholeiites occur in the volume contained within the clinopyroxene-orthopyroxene-plagioclase-olivine tetrahedron. The varieties of quartz normative tholeiite are contained within the volume of the clinopyroxene-orthopyroxene-plagioclase-quartz tetrahedron. If the



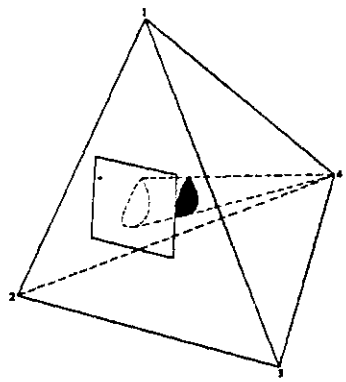
Exploded view of generalized simple basalt system illustrated in upper right inset. Entered are names of rocks whose major normative phases are contained in the tetrahedra. Names underlined are within the tetrahedra. Names in faces are written parallel to base. Lherzolite is in Ol–Cpx–Opx face. An additional inset, Ol–Cpx–An, gives alternative nomenclature when plagioclase is rich in An. After Yoder and Tilley (1962).

Figure 4. Diopside-Olivine-Nepheline-Quartz Tetrahedron (After Wilkinson, 1968).

tholeiites crystallized in equilibrium, this tetrahedron represents the limits of the composition of the original liquids which crystallized into the subsequent different tholeiitic compositions.

The complete range in chemistry of all basalts is very small. Figure 5 shows a representation of thousands of chemical analyses on basalts. The total range forms a small volume located near the center of the Di-Fo-Ne-Q tetrahedron. Only slight changes in the initial composition of a basalt liquid would produce rocks which crystallize in completely different tetrahedra and have different normative mineralogic composition. The natural basalt system is of course more complex than the ideal tetrahedron but the tetrahedron approximates the different differentiation paths which a magma may follow. Upon cooling, pyroxenes in tholeiites exsolve into the various pyroxenes, developing twinned lamellae. This exsolving is almost never seen in alkali olivine basalts (Wilkinson, 1968).

Textural relationships indicate an order of crystallization for the various mineral phases of a typical tholeiite. For the case of olivine tholeiite, olivine reacts with the melt to produce pigeonite which is inverted to bronzite (Wilkinson, 1968). Poldervaart (1946) observed olivine crystals in a tholeiite that were surrounded by successive shells of pigeonite, orthopyroxene, and augite. The augite also showed normal zoning to a more iron-rich subcalcic augite.



Factor measurements for 1996 rocks of basaltic composition. The values recorded for each oxide represent the proportional significance of that oxide in determining the composition of the appropriate end member.

End member	Composition											
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O^+
1	.471	−.086	.771	.066	−.301	−.001	−.346	.118	.076	.017	.003	.011
2	.279	.059	−.035	.156	.119	.002	.735	.518	−.016	−.007	.026	.052
3	.430	.185	−.077	.013	.780	.008	−.373	−.016	.035	.003	.011	.004
4	−.627	.115	.373	.234	.316	.004	−.142	.521	.014	−.031	.051	.050

Figure 5. Tetrahedron Showing the Total Range in Chemical Composition for Basalt Systems (After Manson, 1968)

In slowly cooled tholeiites, pyroxenes exsolve into a variety of structures. Orthopyroxene lamellae exsolve parallel to (100) and clinopyroxene lamellae exsolve parallel to the (001) plane. A combination of both exsolutions produce twinning and a characteristic "herringbone structure" (Wilkinson, 1968). Excess calcium ions in orthopyroxene exsolve into irregular blobs of diopsidic clinopyroxene due to the inversion of pigeonite to orthopyroxene prior to unmixing (Walker & Poldervaart, 1949).

Olivine is not very common in tholeiitic dolerites (by definition) and, when present, olivine occurs as phenocrysts and is confined mainly to chilled contacts. Early olivine Fa_{15-25} is generally unzoned, and many of the olivine crystals show a pyroxene reaction rim. Plagioclase compositions generally range from An_{50} to An_{70} with phenocrysts as calcium rich as bytownite. Normal zoning of more calcic plagioclase to andesine-oligoclase is common. Some tholeiites exhibit reverse zoning as compared to the normal zoning of olivines in alkali olivine basalts (Tomkeieff, 1929). Tholeiite basalts also show a more complex and variable pyroxene assemblage than do alkali olivine basalts. Tholeiites which are rapidly cooled contain a glassy mesostasis which is preserved most often in dikes and chilled facies of layered intrusions (provided the intrusion is not older than a few tens of millions of years). During slow cooling, the glassy mesostasis may be replaced with a quartz-alkali feldspar

mesotasis (micropegmatite). Quartz has also been observed interstitially in some quartz normative tholeiites.

The prefix, olivine, is attatched to tholeiite when describing a tholeiitic rock with olivine phenocrysts. The relative amount of phenocrysts indicates the amount of pre-injection crystallization which has occurred in the magma. The more mafic differentiates of tholeiites include tholeiitic picrites (Poldervaart, 1944). Ophitic and subophitic textures are typical of many dolerites (tholeiites and alkali basalts) as well as for many other basalts (Johannsen, 1937).

In general dolerites are composed of augite, orthopyroxene, calcic plagioclase, opaque oxides, and quartzofeldspathic ground mass. Minor or accessory mineralogy includes apatite. Secondary anorthite (An_{89-92}) has been reported (Wilkinson, 1968).

The ground mass in many of the more slowly cooled dolerites consists of up to 30% quartz-alkali feldspar intergrowths. The ground mass is also charged with opaque oxides and incipient fibrous growths of feldspar and pyroxene. The opaques are predominately magnetite and ilmenite. Biotite occurs only as a reaction product mantling opaques or pyroxene. Apatite is a constant accessory mineral to dolerites (Wilkinson, 1968).

Texturally, tholeiitic dolerites are classed into three groups according to Tomkeieff (1929): a fine-grained basaltic type which occurs along upper and lower cooling

selvages of sills, a normal and dominant dolerite which is a medium grained diabasic rock, and a coarse-grained gabbroid type, which occurs in bands in sills and toward the centers of wide dikes. Textural relationships suggest cooling has occurred from the outside to the inside for the dikes in Georgia.

The dolerites of eastern North America show a differentiation series similar to other tholeiites, and it is implied that the dolerites of eastern North America evolved much in the same fashion as other basalts. The larger dikes show classical differentiation trends with increasing acidity toward their centers. The variation is due to enrichment of residual liquid in silica toward the center leaving behind more mafic margins (Ragland, Rogers, and Justus, 1968).

Major Elements

Weigand and Ragland (1970) and Smith et al. (1975) have characterized the major element chemistry of the Mesozoic dolerites in eastern North America. Weigand and Ragland's study was the most comprehensive and incorporated studies of dolerite dikes from Alabama to Nova Scotia. Smith et al. studied the geochemistry of dolerites and basalts in Pennsylvania, including flows, sills, and dikes. Smith et al. show results reasonably comparable to those of Weigand and Ragland. Table 1 shows the results of major and minor elemental analyses for Weigand and Ragland's study.

Table 1. Major and Minor Element Abundances for Eastern North American Dolerites
(After Weigand and Ragland, 1970)

	1		2		3		4	
	$\bar{x}$	± s	$\bar{x}$	± s	$\bar{x}$	± s	$\bar{x}$	± s
SiO_2	52.69	1.11	52.10	0.62	51.66	1.12	47.90	0.89
TiO_2	1.14	0.11	1.12	0.05	0.76	0.05	0.59	0.11
Al_2O_3	14.21	0.96	14.22	0.55	14.95	0.37	15.26	0.93
Fe_2O_3*	13.87	1.30	11.65	0.34	11.77	0.40	12.10	0.97
MnO	0.22	0.02	0.19	0.05	0.20	0.01	0.18	0.01
MgO	5.53	0.54	7.41	0.46	7.44	0.39	10.52	1.72
CaO	9.86	0.51	10.66	0.40	10.80	0.38	10.75	0.60
Na_2O	2.51	0.16	2.12	0.17	2.23	0.16	2.00	0.29
K_2O	0.64	0.18	0.66	0.15	0.48	0.15	0.29	0.15
Co	52	5	49	3	53	3	65	7
Cr	94	32	277	56	218	36	766	414
Cu	74	41	111	6	68	7	108	22
Li	18	9	19	10	16	8	12	6
Ni	34	15	81	8	48	11	308	115
Rb	22	9	21	6	15	5	8	4
Sr	178	53	186	16	127	12	115	27
Zn	99	7	84	9	86	5	84	7
Zr	94	20	92	8	60	9	50	13

1 High-Fe_2O_3* quartz-normative tholeiite

2 High-TiO_2 quartz-normative tholeiite

3 Low-TiO_2 quartz-normative tholeiite

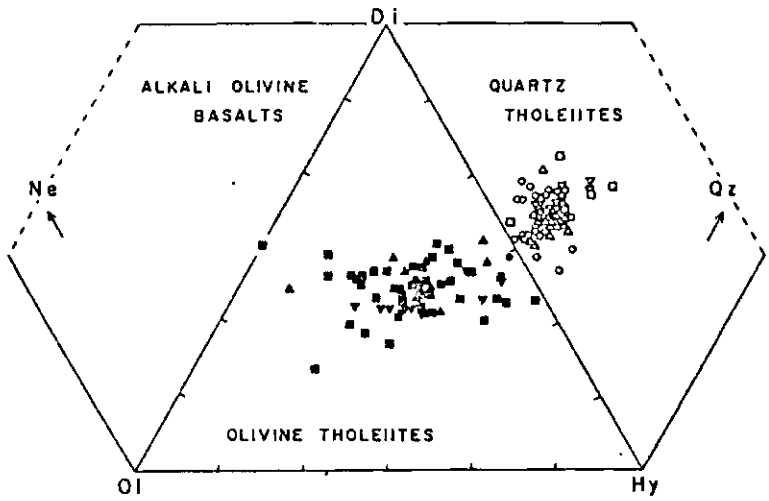
3 Olivine-normative tholeiite

Major Oxides given in weight percent: Minor elements in ppm.

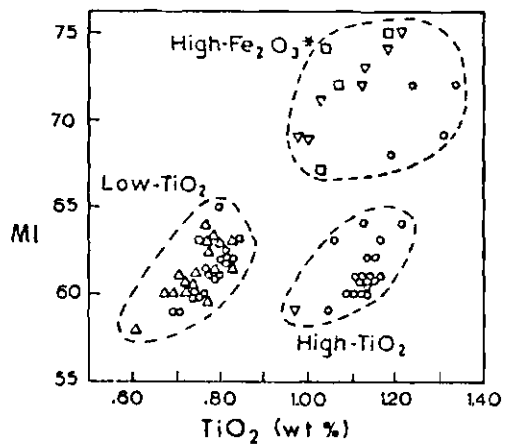
The prevailing data suggest that the dolerites fall into four chemical groupings on the basis of their major element and TiO_2 distributions. These groups are: olivine normative tholeiite, low TiO_2 quartz normative tholeiite (low-Ti), high TiO_2 quartz normative tholeiite (high-Ti), and high Fe_2O_3, high TiO_2 quartz normative tholeiite (high-Fe). The distribution of samples between olivine normative and quartz normative groups is shown in Figure 6a (Weigand and Ragland, 1970). Weigand and Ragland (Figure 6b) show the further division of quartz normative tholeiites using a plot of mafic index (Fe_2O_3*/Fe_2O_3* + MgO) versus TiO_2 (Fe_2O_3* is total iron reported as Fe_2O_3). TiO_2 is a good indicator of chemical class for quartz normative tholeiites. The more differentiated basaltic magma becomes enriched in TiO_2 as SiO_2, H_2O, and the incompatible elements whose ionic radii and chemical valence do not allow them to become easily incorporated into the more dense silicate minerals in the lower crust and upper mantle (Green and Ringwood, 1967).

Implications of Petrology and Major Element Chemistry

Petrologists agree generally that the quartz normative tholeiitic compositions must develop by differentiation from an olivine tholeiitic magma or a liquid from which an olivine tholeiitic magma is derived. This differentiation is thought to occur at crustal depths of less than 15 km (Weigand and Ragland, 1970). Kushiro (1968) has suggested that the quartz tholeiitic composition can be produced over a variable range



a. Normative mineralogy plotted on a diopside-hypersthene-olivine-nepheline-quartz diagram. Solid symbols = olivine-normative, open symbols = quartz-normative. Connecticut-Pennsylvania (○). Virginia (▽). North and South Carolina (□). Georgia-Alabama (△)



b. Plot of TiO_2 versus mafic index ($MI = Fe_2O_3^*/Fe_2O_3^* + MgO$) for the quartz-normative dikes. Connecticut-Pennsylvania (○). Virginia (▽). North and South Carolina (□). Georgia-Alabama (△)

Figure 6. Ne-Di-Ol-Q Tetrahedron Showing Chemical Composition of eastern North American tholeiites. A plot of MI versus TiO_2 shows the quartz tholeiite chemical subdivisions. (After Weigand and Ragland, 1970).

in pressure in the presence of water. Weigand and Ragland assumed that the magmas are relatively dry, and set up an algebraic model relating the cumulate phase to the liquid phase. A summary of their calculations, based on the parental olivine normative composition show that quartz tholeiitic compositions can be derived. For any of the quartz tholeiites, 60-70% accumulated crystals consisting of 52% plagioclase (An_{66}), 25-30% olivine (Fo_{65}), and about 16% diopside ($WO_{52}En_{33}Fs_{15}$) are required of the olivine tholeiitic magma to produce a liquid of quartz tholeiitic composition upon fractionation. These calculations led Weigand and Ragland to suggest that at least two of the quartz normative types were derived from olivine normative tholeiitic parental magma and that they must have been derived in two distinct events, because they could not derive a low-Ti quartz normative tholeiite from an olivine tholeiite magma and subsequently derive the high-Ti quartz normative tholeiite from the low-Ti quartz normative tholeiite. Thus, either the two quartz tholeiites were possibly derived from similar parental magmas which followed two slightly different crystallization paths, or the two quartz normative tholeiites were derived from different parental magma.

Green and Ringwood (1967) suggested that the primary magmas, from which basalts evolve, originate in the upper mantle at a depth between 35 and 100 km. They also state that 30% partial melting of a pyrolitic source (a hypothetical

rock composed of 1/4 basalt and 3/4 peridotite) in the 35 to 100 km depth range would produce picritic olivine tholeiitic magmas which differed from one another only in incompatible element contents. The liquid (produced by partial melting) being less dense than the upper mantle, ascended with settling of some of the olivine crystals, intruded tensional fractures, and produced the olivine normative tholeiite dikes observed today (Weigand and Ragland, 1970).

Weigand and Ragland suggest that the olivine tholeiitic magma, if parental, must have partially ponded in the crust and, due to the increased residence time in the crust as a liquid, the olivine tholeiitic magma fractionated to a quartz tholeiitic composition by removal of 60-70% cumulate minerals, plagioclase (50-55%), olivine (25-30%) and clinopyroxene (15%). The ascent and concomitant ponding of olivine thoeliitic magmas and fractionation to quartz tholeiites is suggested by Weigand and Ragland to be the mechanism which produces the observed four tholeiitic compositions.

Spatially, Weigand and Ragland pointed out that the high-Ti and low-Ti quartz normative tholeiites are found in Connecticut and Pennsylvania. High-Fe tholeiites are found in Connecticut as well. Olivine tholeiites, high-Ti quartz tholeiites and High-Fe quartz tholeiites occur in Virginia and North Carolina in equal amounts. Only olivine tholeiites are found in South Carolina. Weigand and Ragland found only olivine tholeiites and low-Ti quartz tholeiites in Georgia

and Alabama.

The spatial distribution of tholeiites was suggested by Weigand and Ragland (1970) to be controlled by the tectonic environment into which the dolerites intruded in Early Mesozoic times. The magmas in southeastern North America encountered tensional fractures which were open and allowed the tholeiitic magma to ascend rapidly with little time from fractionation, with the exception of magma from a diapir of deep origin. It must have ponded in the crust under present day Georgia to explain the presence of quartz tholeiites. Weigand and Ragland further suggested that the shear fracture systems (DeBoer, 1968) in northeastern North America were closed at the time the tensional fractures were open in the southeast,and thus to the northeast, the tholeiitic magma ponded in the upper crust (less than 15 km). An additional tectonic event was envisioned which subsequently opened less numerous fractures in the northeast, after the magma had evolved to a quartz normative composition, allowing formation of dikes and sills of quartz normative tholeiitic compositions.

Weigand and Ragland suggested that magmas of the two main quartz tholeiite compositions must have been available for intrusion over an extended period of time since both compositions are represented in dikes as well as sills in Pennsylvania. Van Houten (1969) observed that the dikes generally postdate sill intrusion because some dikes commonly extend

beyond the borders of the Triassic basins but are not offset along the basins' faulted borders. Thus, he concluded that the dikes are younger than sills, flows and the subsequent tilting, faulting, and folding of the Triassic basins. Weigand and Ragland (1970) envisioned several diapiric episodes to account for the existence of quartz normative tholeiitic magmas which were available for intrusion over a long period of time.

Smith et al. (1975) suggested a different sequence of events concerning dike and sill intrusion, based on field and laboratory observations made on Pennsylvania dolerites. They recognized three types of dolerites in Pennsylvania; the Quarryville type (olivine normative tholeiite), the Yorkhaven type (quartz normative tholeiite with higher Ti and Cu) and the Rossville type (quartz normative tholeiite with lower Ti and Cu). On the basis of geologic field observations, calculated cooling rates, and paleomagnetic data, they concluded that each chemical type was emplaced within a fairly short period of time and that all sheets, dikes and flows of the same chemical composition were coeval. They suggested an order of intrusion from the oldest to the youngest to be the Quarryville type, the Yorkhaven type, and the Rossville type.

Smith et al. believe that the two quartz normative tholeiites could be formed by crystallization of 30-40% of olivine tholeiitic magma (this cumulate amount is distinctly lower than Weigand and Ragland's proposed 60-70%) and sub-

sequent assimilation of orthopyroxene from the mantle.

Minor Elements

In general, the trace elements of the eastern North America dolerites can be seen to vary with mafic index (MI). Cr and Ni strongly decrease with increasing mafic index; Co slightly decreases with respect to MI; Cu, Rb, Zn, and Zr slightly increase with respect to MI. Sr moderately increases and Li shows no simple trend with respect to mafic index (Weigand and Ragland, 1970). Table 1 includes abundances of trace elements for tholeiites in eastern North America. The trace element data of Weigand and Ragland suggest that for TiO_2, Cr, Cu, Ni, Rb, Sr, and Zr, there is little overlap in composition between the high-Ti and low-Ti quartz normative tholeiites. The low-Ti quartz normative tholeiite is intermediate between the high-Ti quartz normative and olivine normative tholeiites with respect to most trace elements with the exception of Cr, Cu, and Ni which are distinctly lower in the low-Ti quartz normative tholeiites than the other two types.

Weigand and Ragland (1970) suggest that there is statistically no difference in K/Rb of olivine tholeiites and the quartz normative tholeiites. Low $^{87}Sr/^{86}Sr$ ratios (0.704-0.706) for olivine normative and high-Ti quartz normative types suggested to Weigand and Ragland that little if any contamination with respect to Sr by crustal material oc-

curred after magma formation. This conclusion was supported by the observation of uniform sulfur isotopic composition of dikes from Connecticut to Pennsylvania (Smitheringale and Jensen, 1963).

Smith et al. (1975) used Sr data produced by Gast (1967) on dolerites similar to their Yorkhaven type which showed an average initial $^{87}Sr/^{86}Sr$ ratio of 0.706. Assuming that primary olivine tholeiitic magma was similar to oceanic basalt with a $^{87}Sr/^{86}Sr$ ratio of 0.703, Smith et al. calculated that the Yorkhaven magma could have assimilated as much as 20% of the country rock. They suggested that the Rossville type assimilated little or no elements from the country rocks.

Weigand and Ragland invoked Green and Ringwood's (1967) concept of vertical chemical inhomogeneity resulting from the upward migration of incompatible elements to explain the trace element distribution data. Smith et al. favor the contamination of quartz tholeiitic magma by assimilation of country rock to explain the trace element distribution.

Partial melting of different levels in the asthenosphere is suggested to produce diapirs (Green and Ringwood, 1967). The diapirs originating at deeper levels could be depleted in the incompatible elements due to the tendency of large ionic radii elements to migrate upward in the mantle and crust. Heier et al. (1965) and Compston et al. (1968) have studied processes of selective contamination by diffu-

sion processes to explain some of the high $^{87}Sr/^{86}Sr$ ratios and high contents of incompatible elements in some tholeiites. They suggest that the increased vapor phase from the relatively wet country rocks into which the dolerites intrude might be the mechanism for selective diffusion of certain chemical species into a magma. The incompatible elements (K, Ti, P, Rb, Cs, Ba, Th, U, and the light rare earth elements) should chemically fractionate into the magma because they are the most mobile.

Smith et al. (1975) view the retention of large homogeneous magma bodies for geologically long periods of time in the crust or upper mantle without chemical change to be improbable. Evidence against long periods of storage in the crust without chemical change can be seen by observing the Ni contents of the tholeiites. Crystallization of olivine depletes the remaining magma in Ni. They suggest that storage of a homogeneous unfractionated body of magma in the crust for even 20,000 years is unlikely. The lack of significant difference in Ni content between sheets, dikes, and flows of the same chemical type suggests that all three forms of igneous activity were emplaced from a homogeneous magma, and a maximum time interval between magmatic events would be a few thousand years.

Smith et al. attempted to explain the observed distribution of trace elements in the various tholeiitic types. They pointed out that Jamieson and Clark (1970) envisioned

two parents of the two quartz normative compositions originating by partial fusion in the same region of the mantle but at different times. The first magma would deplete the mantle from which it evolved in incompatible elements and would be richer in these elements than a subsequent partial melt and second magma generation from the same region. Smith et al. revised this idea by invoking assimilation of crustal material during the ascent of a Yorkhaven magma toward the surface and suggested that later batches of magma (Rossville) did not assimilate elements from the same part of the crust (possibly because of a more rapid injection) or that the later magma passed through the same area of the crust or mantle in which the first magma did and found that area depleted in incompatible elements. Green et al. (1967) suggested that the high Al content of the Rossville type constrained the magma to having formed at greater depths than the Yorkhaven type. Using Green and Ringwoods's concept of vertical inhomogeniety of the mantle, there would have been fewer incompatible elements at deeper levels from which the Rossville magma may have evolved.

The trace elements along with major elements, petrology, geochemistry, geochronology, and geology which have been presented in this chapter place many constraints on any model which proposes to reconstruct correctly the sequence of events which rifted North America from South America and Africa. There are many conflicting ideas within the litera-

ture to date. The K-Ar relationships of the dolerite dikes of the Georgia Piedmont should help further constrain the tectonic models which can be developed. To understand the constraints developed from K-Ar relationships a clear picture of the K-Ar dating methods and analytical procedures must be developed. This is the subject of chapter two in this paper.

CHAPTER II

PROCEDURES AND ANALYTICAL METHODS

K-Ar GEOCHRONOLOGICAL METHODS

Principles of K-Ar Age Measurements

^{40}K is a naturally occurring, radioactive nuclide which decays either to ^{40}Ca or to ^{40}Ar (Dalrymple and Lanphere, 1969). Most of the disintegrations (88.8%) are β^- disintegrations producing ^{40}Ca in its ground energy level. The remainder of the nuclear disintegrations involve electron capture or β^+ emissions which produce ^{40}Ar. The electron capture process is responsible for 11% of the disintegrations and leads usually to the production of an excited state of ^{40}Ar which subsequently decays to the ground state by γ emission. A small fraction (0.16%) of the ^{40}K disintegrations involve electron capture directly to the ground state of ^{40}Ar. A negligible amount (0.001%) of the nuclear disintegrations involve β^+ emission. Dalrymple and Lanphere (1969) have discussed the details of K-Ar geochronology, so the general theory of the method will only be outlined here.

The fundamental assumptions used in the K-Ar method and the mathematical derivations of decay equations should be understood and are presented here. It is well established that radioactive nuclides obey an exponential decay law given

by the equation:

$$N = N_o e^{-\lambda t}, \tag{1}$$

which states that the number, N, of atoms present at any given time, t, is a function of the initial number, N_o, of atoms (number of atoms present when t = 0). This equation is valid provided that there is no loss or gain of parent except that which occurs by radioactive decay and provided that the decay constant, λ, does not vary. If the daughter atoms are stable and are not produced by any process other than decay of the parent, it follows that under closed conditions, the decrease in the number of parent atoms is exactly equal to the increase in the number, D, of daughter atoms. This relationship is given in the equation:

$$\delta D/\delta t = -\delta N/\delta t, \tag{2}$$

where again D is the number of daughter atoms and N is the number of parent atoms. If the symbol D_{rad} is used to represent the number of stable daughter atoms formed by radioactive decay within the system since the time, t = 0, then at any later time:

$$N_o = N + D_{rad}, \tag{3}$$

where the subscript rad represents the radiogenic daughter

atoms formed within a specific system. Equations 1 and 3 may be combined, producing the relationship:

$$D_{rad} = N(e^{\lambda t} - 1). \qquad (4)$$

Provided that a system has been closed and there were no initial daughter atoms present, the amounts of daughter and parent nuclides present in the system today may be used to calculate the age of the system. Equation 4 may be used without modification where the radionuclide has a single decay mode producing only one daughter species. Where there is more than one daughter, the equation may be rewritten in terms of one of the daughters.

In the case of the K-Ar method, the appropriate modification is as follows: Equation 4 becomes

$$D_{1_{rad}} + D_{2_{rad}} = N\{e^{(\lambda_1 + \lambda_2)t} - 1\}. \qquad (5)$$

For the specific case of ^{40}K decay;

$$^{40}Ar_{rad} + {}^{40}Ca_{rad} = {}^{40}K\{e^{(\lambda_\varepsilon + \lambda_\beta)t} - 1\}, \qquad (6)$$

where λ_ε is the electron capture decay rate of ^{40}K, producing ^{40}Ar; λ_β is the β^- decay rate of ^{40}K, producing ^{40}Ca; and the symbols for the nuclides now represent the numbers of atoms of each species. (In this and following quantitative relationships, an isotopic symbol will normally be used to denote the

amount of the isotope. For example, in this equation $^{40}Ar_{rad}$ denotes the number of atoms of radiogenic ^{40}Ar, and ^{40}K, the number of atoms of ^{40}K. Whether such a symbol names the material, or means the amount of such material, should be clear from the context.) Using the relationship:

$$^{40}Ca_{rad}/^{40}Ar_{rad} = \lambda_\beta/\lambda_\varepsilon, \qquad (7)$$

Equations 6 and 7 can be combined to produce the equation:

$$^{40}Ar_{rad} = {}^{40}K\,[\lambda_\varepsilon/(\lambda_\varepsilon + \lambda_\beta)][e^{(\lambda_\varepsilon + \lambda_\beta)t} - 1]\,. \qquad (8)$$

To calculate age, Equation 8 may be re-written explicitly in terms of time:

$$t = [1/(\lambda_\varepsilon + \lambda_\beta)]\ln\{(^{40}Ar_{rad}/^{40}K)(\lambda_\varepsilon + \lambda_\beta)/\lambda_\varepsilon + 1\}. \qquad (9)$$

Using the decay constants, $\lambda_\beta = 4.72 \times 10^{-10}y^{-1}$ and $\lambda_\varepsilon = 0.585 \times 10^{-10}y^{-1}$, Equation 9 can be simplified to the expression:

$$t = 1885\ \ln\{9.0683\,[^{40}Ar_{rad}/^{40}K] + 1\}, \qquad (10)$$

where t is expressed in units of one million years. In the application of the K-Ar method to rock samples, the total potassium is measured, and it is assumed that $^{40}K/K_{total} = 0.000119$ today; thus the amount of the isotope ^{40}K in the samples can readily be calculated.

Newer decay constants and isotopic abundance for ^{40}K have been recommended by the I.U.G.S. Subcommittee on Geochronology in 1976. The new values ($\lambda_\varepsilon = 0.581 \times 10^{-10} y^{-1}$, $\lambda_\beta = 4.962 \times 10^{-10} y^{-1}$, and $^{40}K/K_{total} = 0.0001167$) have not been used by many laboratories to date, so the age calculation in this work will be presented using both the new and old constants. The new constants will increase the computed age values by 2.3% for 200 m.y. old samples and by less than 2.3% for samples older than 200 m.y.

Provided one can measure the potassium and the different isotopes of argon present in a rock or mineral, the age can be calculated if the basic assumptions of the method are valid. Dalrymple and Lanphere (1969) discussed five fundamental assumptions of the conventional K-Ar method: 1) The decay of ^{40}K occurs at a constant rate regardless of the chemical or physical environment. 2) The present day $^{40}K/K_{total}$ ratio is the same in all materials to which the K-Ar method is applied. 3) All the ^{40}Ar is radiogenic (formed within the system to be dated) or atmospheric and there is no component of excess ^{40}Ar. 4) The rock or mineral must have been a closed system since the time of crystallization and cooling of the rock or mineral (it is this time which is assigned the value of zero, to use the equation above). 5) The time interval of formation of the rock or mineral is short compared to its age. Evaluation of these assumptions is important in discussing the validity of conventional K-Ar apparent ages for sets of samples.

General Procedures

The conventional potassium-argon method involves preparing a rock or mineral sample in two portions; one for the argon analysis and one for the potassium analysis. (There is an inherent problem involved with this step if the rock is inhomogeneous.) The argon sample is sealed in a vacuum system and melted in a furnace. The evolving gas is mixed with a known amount of an isotopic tracer, usually ^{38}Ar, and measured isotopically with a mass spectrometer. K is measured by standard analytical techniques, usually by some sort of spectrophotometry. A series of interlaboratory reference samples have been measured by most laboratories to serve as a check on the reproducibility of the analytical procedures.

Procedures Used in this Work

Sampling of Dolerite Dikes. Samples were collected from as broad a geographic distribution as was obtainable in the Georgia Piedmont. Samples were also collected from two dikes in the Blue Ridge Mountain District and one sill was sampled from well cuttings in the Coastal Plain of Georgia. Samples were collected from 68 sample localities, several across the width and along the strike of most dikes. Multiple samples are necessary to obtain information about any initial argon or argon loss that a dike might have been subjected to. If argon has been lost or if there were initial argon present at the time of crystallization, the isotopic composition of

argon and the ratio of non-atmospheric argon to potassium would be expected to vary across a dike's width and/or along its strike. Figure 7 is a map of actual sample localities. Approximately 300 rock samples were taken from 68 sample localities. Figure 8 shows which of the dikes were the subjects of potassium-argon analyses in this study. Twenty dikes were included in the actual analyses, with at least one sample (collected from the margin of the dike when such a sample was available) from each dike. Three dikes were analysed across their widths. In two cases samples taken from along strike of the dike were dated. The latitude and longitude of sample localities and a brief description of how to get to the localities appear in the Appendix.

In a few cases, country rocks in contact with dikes were collected. Quartz was especially sought to serve as an indicator of extraneous argon in the intrusive environment. There is very little K, and thus there should be very little radiogenic Ar, in the quartz, so extraneous argon (if present) should be easy to identify. Three such quartz samples were found and analysed using the conventional K-Ar method. In an earlier study (Wampler, 1973), a sample of biotite in contact with a dike was provided from the Georgia Piedmont by the Georgia Geological Survey and dated by Wampler. The rationale of the biotite analysis is that the biotite in contact with the dike should have had its K-Ar geochronometer reset as the hot magma intruded and solidified as a dike.

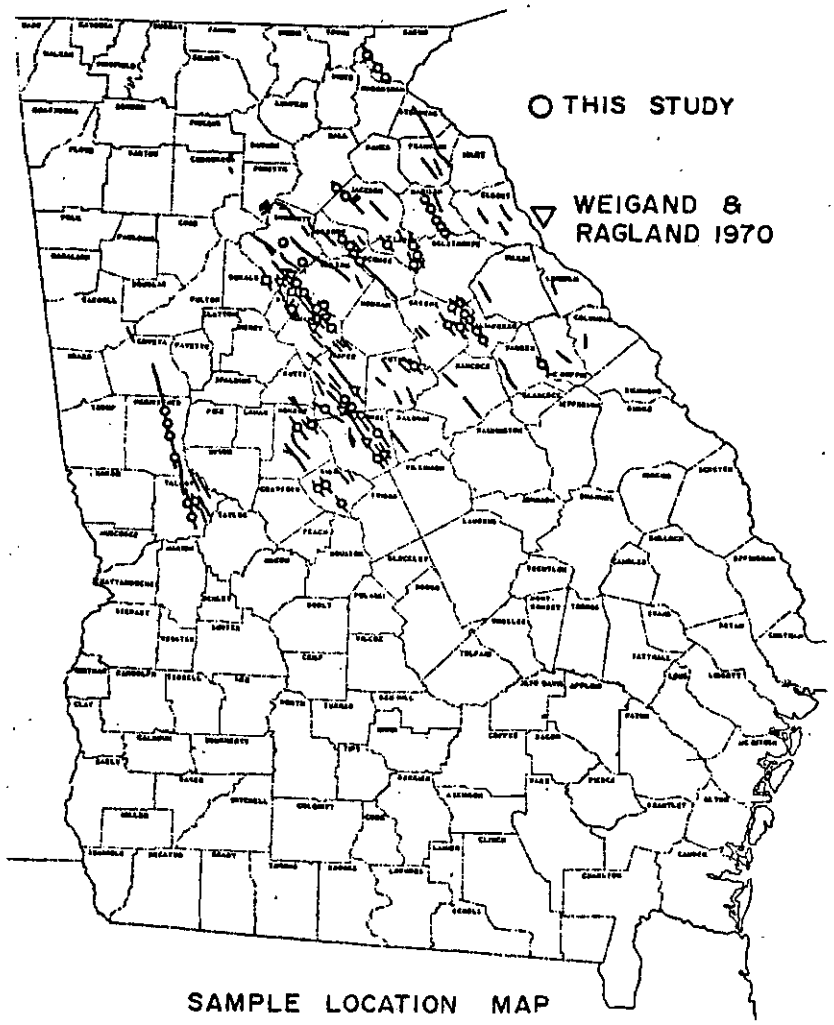


Figure 7. Sample Location Map for all the Localities for which samples were taken.

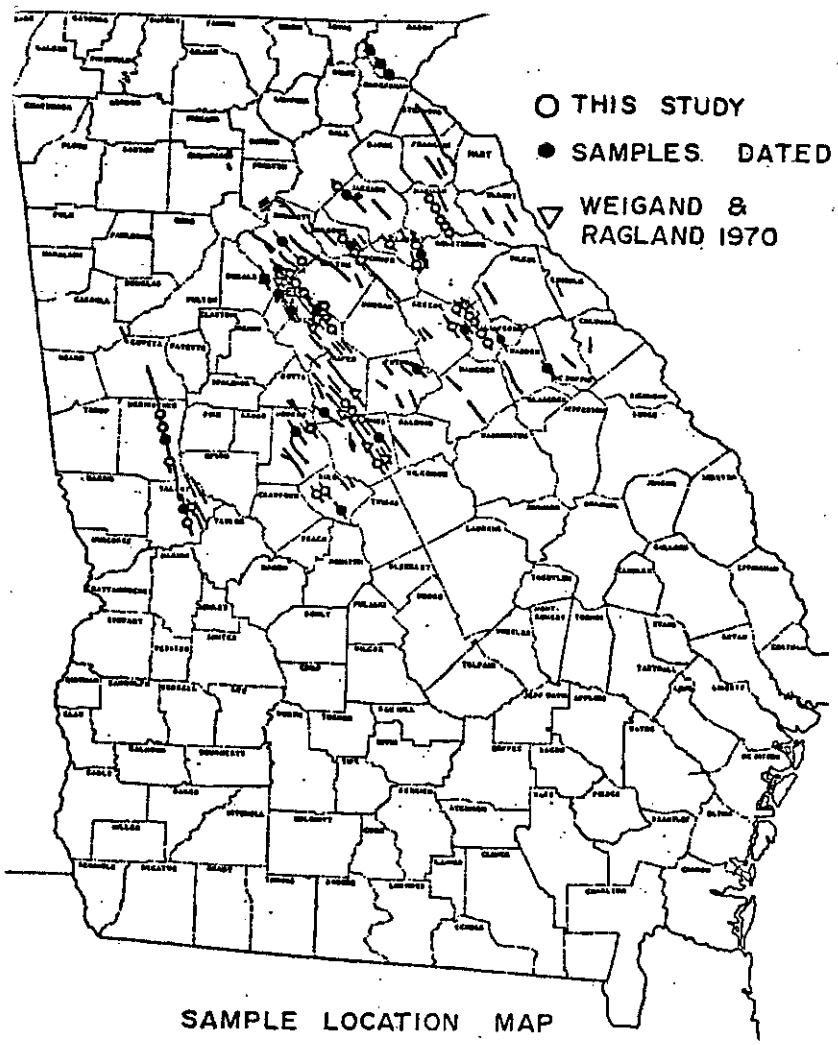


Figure 8. Sample Location Map for Collected and Dated Dolerites of Georgia.

By looking at the argon abundance and isotopic composition from different portions of a rock body and from the rocks that it was in contact with upon crystallization, information about the origin of the argon isotopes in the system may be obtained. Knowledge of this sort will help clarify which K-Ar data are acceptable for the calculations of meaningful geologic ages for the dolerite dikes, and thus for timing the initiation and duration of continental rifting in the Early Mesozoic.

Petrography

A thin-section of each rock to be dated was prepared by slabbing the rock and cutting a rectangular piece out of the slab. The rectangular rock chip was lapped flat and glued to a petrographic glass slide. Most of the chip was then cut off the glass slide and was used as the material in the potassium-argon analysis. The thin-section was then ground and lapped to 0.03 mm thick, as seen by the first order grey to pale yellow color of plagioclase laths under polarized light. A cover slip was glued over the finished thin-section.

Since thin-sections were made of the actual rock specimens dated, petrographic examination of them provides important information about the condition of the rock systems. Modal analyses were done on 20 thin-sections (one for each dike dated) to determine the mineralogy of each rock system and to serve as a screening for secondary mineralization which might

not be apparent in hand specimen. The presence of secondary mineralization suggests that the rock has not been a closed system since crystallization.

A modal analysis is a statistical representation of the amount of each mineral present in a thin-section. The principle of modal analysis is based on construction of a grid over a thin-section, identifying the mineral present at each intersecting point, and cumulatively recording each mineral identified. In banded rocks, the selected plane of the thin-section should only be perpendicular to banding (Hutcheson, 1974). In the case of the Mesozoic dikes, the dolerite samples from near the contact are very fine-grained with a random orientation of pyroxene and plagioclase crystals (and sometimes olivine). The random orientation of the minerals is ideal for a modal analysis and any section taken out of a dolerite with randomly oriented crystals represents a good statistical distribution of the minerals in the rock.

The grid chosen to do the modal analysis was produced by an American Optical point counter with notched wheels and a spring tension pointer which can be engaged or disengaged at will. A total of 1200 points or grid intersections was constructed over each thin-section by using every fourth increment of the notched wheels. The X and Y directions do not have to be equal but the distance between points on the X or Y direction must be equal. The grid was variable depending on grain size of the analysed rock. A grid spacing

of 1/3 mm translation was used for coarse-grained rocks and a grid spacing of 1/20 mm translation was used for fine-grained rocks. Geometric relationships and the statistical basis of the petrographic modal analysis are given in Chayes (1956). An estimated precision of the modal analysis on the basis of 1200 point counts is approximately 5% at the 95% confidence level.

Sample Preparation for Potassium-Argon Analyses

The rock chip, which was cut from thin-sections, was the whole rock material used in the K-Ar analysis. The chip was crushed in a motor driven jaw crusher with ceramic jaws (85% alumina). The crushed sample was pulverized to less than 0.5 mm in a pulverizer with ceramic plates (85% alumina). The sample was divided into two aliquots; one for the whole rock analysis and one for possible mineral separation. The sample for the whole rock analysis was placed in a beaker of water and the fine fraction was decanted off. This was done to cut down on any contamination by dust, to eliminate problems associated with handling fine powders and to reduce the amount of the atmospheric argon component. The grain size (approximately .05-.5 mm) selected appears to be the least contaminated by atmospheric argon (Keeling and Naughton, 1974). Decanting off the fines generally involves loss of a small percentage of the total sample and does not appreciably affect the K-Ar measurements. The removal of the fines produces only

a small effect on the chemical composition (relative to the whole rock) and a negligible effect on the K/Ar ratio (at least for undisturbed samples).

In this study, two lines of experimentation were established to find additional ways to reduce the amount of atmospheric argon adsorbed or trapped on the surface of mineral grains and in microfractures in the grains. One method used controlled preheating of a sample and the other used washing techniques. The washing treatments were used on dolerites collected from Rockingham County, Virginia by Dr. J. M. Wampler. A crushed sample, with the fine fraction removed, was agitated by an ultrasonic probe for 30 minutes after which the fines were removed again. A second aliquot of the same material was washed with warm nitric acid (1 normal) for one hour, with occasional stirring. These samples were analysed isotopically and showed no appreciable difference in the atmospheric argon component in comparison with untreated portions of the same material. Therefore acid washing and ultrasonic dispersion were dispensed with in further sample preparations.

In the controlled heating experiments, five grams of each dolerite sample were wrapped in copper foil and heated for four hours at each of four successively higher temperature levels from 100°C to 400°C. In Figure 9 the solid line represents the total amount of ^{40}Ar released as a function of temperature. A sample of dolerite from Virginia (MWD-21) produced a curve which shows that argon was released in

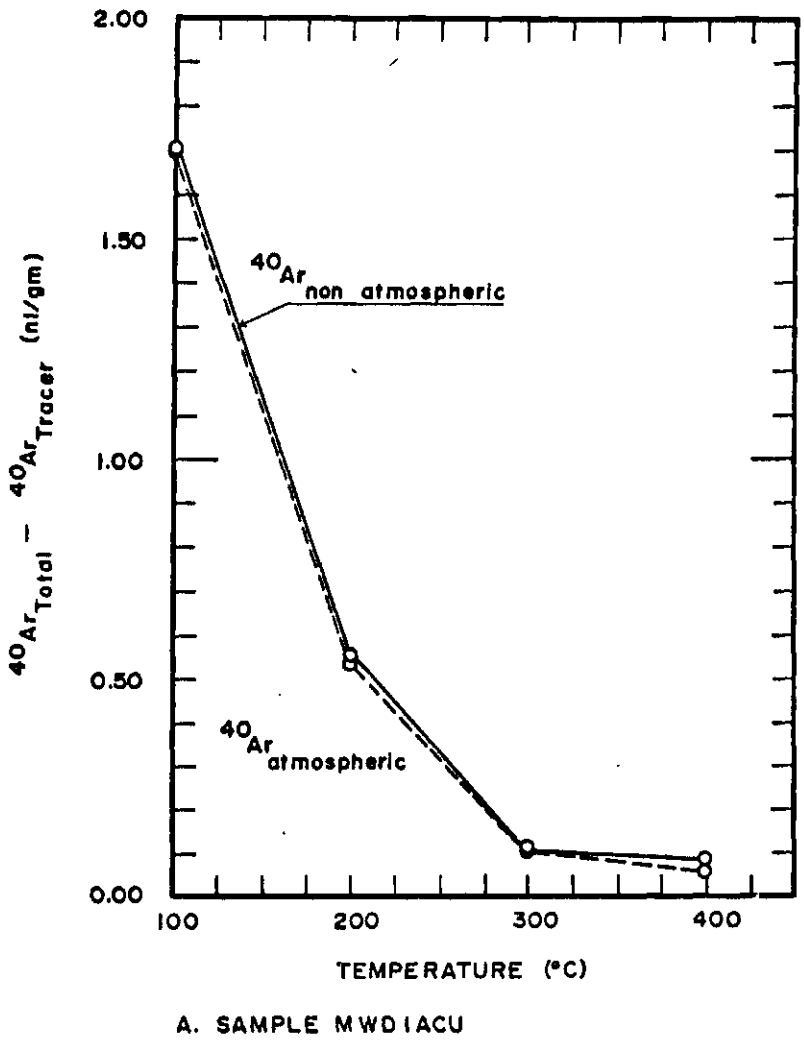


Figure 9. Low Temperature Release of Non-atmospheric Argon for a dolerite from Virginia.

decreasing amount with increasing temperature up to 400°C. The isotopic composition of this argon was indistinguishable from atmospheric argon, except for the 400°C increment which included a small amount of non-atmospheric argon. A similar pattern of argon release was observed for other Virginian dolerites in an earlier, less precisely controlled, experiment. On the basis of these experiments, and the experience of workers in other laboratories, 200°C was chosen as a temperature for overnight prebaking of the samples in this study. It was expected that the prebaking significantly reduces the atmospheric contamination without affecting the radiogenic argon within the samples.

The rock sample with fines removed was used as the analytical sample for the argon and potassium analyses. This sample was divided and re-divided with a sample splitter to obtain approximately equal aliquots of about 1/2 g each, one for the Ar analysis and one for the K analysis. Sample splitting is not a perfect process, and it is suspected that small differences between the two samples may be responsible for problems in the reproducibility of the K/Ar ratio. The aliquot for argon analysis is accurately weighed (to 0.0001g) and is folded into a preweighed capsule of copper foil and dried in an oven at 110°C overnight. The K aliquot is accurately weighed and transferred to an acid washed teflon beaker. The samples are then ready for the individual K and Ar analyses.

Sample preparation was slightly different for mineral separates. (Only two mineral separations were done in this study.) The rock samples chosen were coarse-grained and were crushed and pulverized to pass through a 119μ nitex sieve. The powder was poured into a 50 ml beaker filled with tetrabromoethane with a density at 20°C of 2.96 g/cm^3. The lighter plagioclase fraction floated and the pyroxenes, olivine, ilmenite, and sulfides settled to the bottom. The plagioclase fraction was separated by decanting the top fraction from the beaker, and was then rinsed with acetone and dried. The two separates, light and heavy, were then ready for individual K and Ar analyses. It is estimated that the plagioclase mineral separates were 95% pure on the basis of x-ray diffraction analyses.

Potassium Analysis

The K analysis is done by atomic absorption spectrophotometry. The aliquot for K analysis was dissolved in a mixture of hydrofluoric and perchloric acids (3:1 by volume) in teflon beakers which were covered and heated overnight at 150°C. The silicon evolves as SiF_4, a gas. After removing the cover and increasing the hot plate temperature the solution is allowed to evaporate almost completely (to be sure that the final K solution in each sample has approximately the same viscosity). The K and other cations are precipitated as perchlorate salts. The perchlorate salts are taken

up into a diluting solution of 4% nitric acid (by weight) which contains NaCl (0.1% by weight) and removed to a prewashed and preweighed polyethylene bottle with a cap to prevent evaporation and spillage. The bottle and solution are then weighed to 0.1 g on a top loaded balance. The weighing is done in order to calculate dilution factors.

A set of standard solutions of known K content are also prepared. Standards of 50 ppm, 10 ppm, 5 ppm, 4 ppm, 3 ppm, 2 ppm, 1 ppm, and 0 ppm K were prepared, where 1 ppm is equivalent to 1 microgram of K per gram of solution. The 50 ppm K standard solution was prepared by solution of a precisely weighed amount of KCl. The other standards were made by the proper dilution of the 50 ppm solution in acid washed, preweighed polyethylene bottles with caps.

The K analyses were done in this study with a Perkin Elmer (model 303) atomic absorption spectrophotometer. Standard texts on this subject describe the principles of operation and theory of atomic absorption spectrophotometry (Slavin, 1968; and the ASTM Standard Book on Emission Spectroscopy, 1971).

Briefly, standards and sample solutions are aspirated through a fine polyethylene tube into an acetylene-air flame. A K hollow cathode lamp produces a beam with the K emission spectrum which is aligned through the flame. The K atoms in the solution are vaporized in the flame and absorb their characteristic spectrum from the K lamp. The absorbance, or a number

proportional thereto, at a selected wavelength, is measured electrically with an automatic readout, four digit, concentration-reading digital voltmeter. The spectrophotometer was operated at a wavelength of 766.5 nm with a collimator slit setting of 4 (a slit width of 1.0 mm). The source current used with the K lamp was 10 ma. The system has an approximate detection limit for K of 0.005 ppm and a sensitivity of 0.1 ppm per 1% absorption.

A preliminary run of samples is done to determine K content approximately, so that samples may be further diluted to the 2-3 ppm range, which is the ideal concentration to measure K with the atomic absorption spectrophotometer. In the final K analysis, a voltage proportional to absorbance is read in the concentration mode, and the relative absorbances of standards are plotted versus the absolute concentrations of the standards. A best-fitting (by least squares) cubic curve is determined by computer, and the K concentrations (in ppm) of the samples are calculated from this working curve. The K concentration in each solution is converted to % by weight for the preliminary samples from the dilution factor previously determined for each sample. The samples were randomly lined up with a standard every five samples, and the order of running them was reversed after each runthrough to help eliminate problems of drift in the system response. Each sample was measured four times in each run, and duplicate runs were done to improve the analytical precision of the K values. The

analytical precision is estimated to be 1% at the 95% confidence level.

The Conventional Argon Isotopic Analysis

The aliquot for Ar analysis, wrapped in a capsule of copper foil, is heated at 110°C overnight. The capsule is reweighed to determine how much water was lost at 110°C. This provides a correction for water loss applied to the K sample weight. The sample is then loaded into an argon extraction system (Figure 10). The sample is prebaked under vacuum at about 200°C overnight to eliminate a significant proportion of the atmospheric argon contamination.

The Ar aliquot is melted in a resistance-heated furnace under a high vacuum to form a viscous silicate melt at approximately 1150-1200°C. The furnace and sample storage area constitute the fusion system in Figure 10. Evolving gases expand through two cold traps into Purification System number 1 (PS-1) which has been isolated to contain the gases. A "spike" of ^{38}Ar (greater than 99% purity) of known volume is added to the closed system from a bulb reservoir just before sample fusion. The cold traps between the fusion system and PS-1 freeze out H_2O and CO_2. The first trap is cooled by melting ethanol (161 K) which freezes out water without adsorbing or trapping Ar atoms. It has been established by Wampler and Yanase (1974) that freezing water at liquid nitrogen temperature (77 K) lends to trapping argon within the ice.

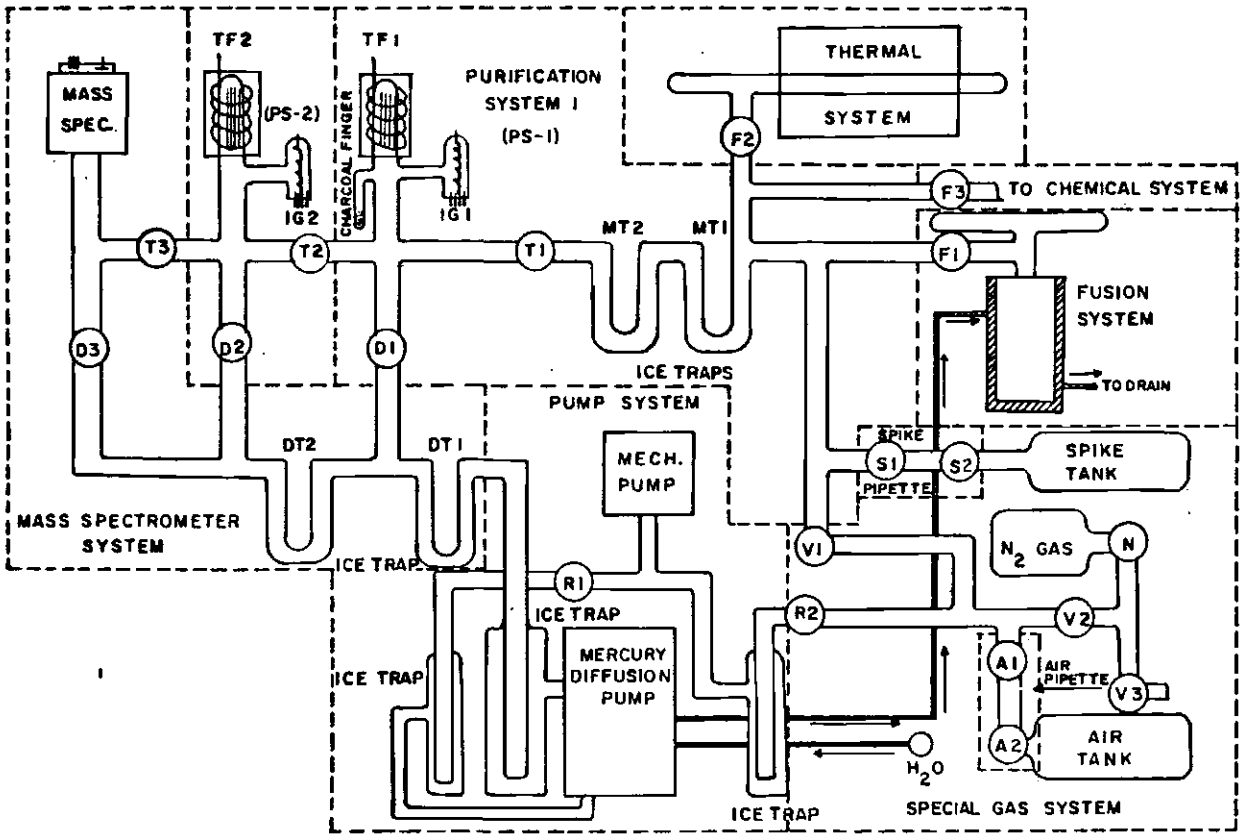


Figure 10. Diagram of the Argon Extraction Line and Mass Spectrometer at Georgia Institute of Technology as of the end of 1975.

The trapped argon can be a significant fraction of the total sample if two cold traps were not used. The second trap is cooled by liquid nitrogen to freeze out CO_2 and any water molecules or other condensible gases which might have escaped the melting ethanol trap.

A titanium getter (fused quartz finger containing Ti metal strips) is cooled from 800°C in PS-1 to react with reactive gases such as H_2, N_2, CO, and others. Thus with cold traps and the process of gettering the gas sample is cleaned of most of its condensible and its reactive components. After the first purification, the sample is allowed to expand into Purification System number 2 (PS-2) where a second Ti getter reacts with traces of reactive gases which might still be present after the first purification. The total gas pressure decreases as the reactive components and condensibles are removed and the decrease is monitered with ionization guages in PS-1 and PS-2. After the sample has expanded into PS-2, this portion of the system is isolated from the earlier stages, and purification continues until the pressure in PS-2 is less than 5×10^{-5} torr, a pressure range which is compatible with the operation of the MS 10 mass spectrometer.

A detailed description of the MS 10 mass spectrometer is given by Farrar, MacIntyre, and York (1964). The MS 10 has a sensitivity of 5×10^{-5} amperes/torr for argon, and a resolving power of about 50. The MS 10 at Georgia Tech has been modified to give higher resolution. The MS 10 at Georgia Tech

is connected on-line with the argon extraction and purification system. This mode of operation saves considerable time in the analyses because no glass blowing and opening of the vacuum system to atmospheric pressure is required to transfer the purified, spiked gas. Two traps are used on the side of the mass spectrometer which is connected to a two stage mercury diffusion pump. These traps are cooled by liquid nitrogen when the system is being operated in a procedure that will involve opening the mass spectrometer to any of the other systems. The cleaned gas sample is admitted to the mass spectrometer in the static mode; that is, the mass spectrometer is isolated from the pumping system, and the gas sample is allowed to expand into the mass spectrometer. Before admitting the gas, the background between mass numbers 35 and 41 is scanned to be sure no significant background signal is present in this mass range.

A Cary vibrating reed electrometer is used to detect the small currents produced by accelerating ionized atoms through a magnetic field in the mass spectrometer. The electrometer output voltage is recorded on a strip-chart recorder. The height of the peak at each mass number, when multiplied by a scale factor, is proportional to the ion current of the corresponding argon isotope, which is in nearly constant proportion to the amount of the isotope present in the ionization chamber of the mass spectrometer. A typical argon scan is shown in Figure 11a.

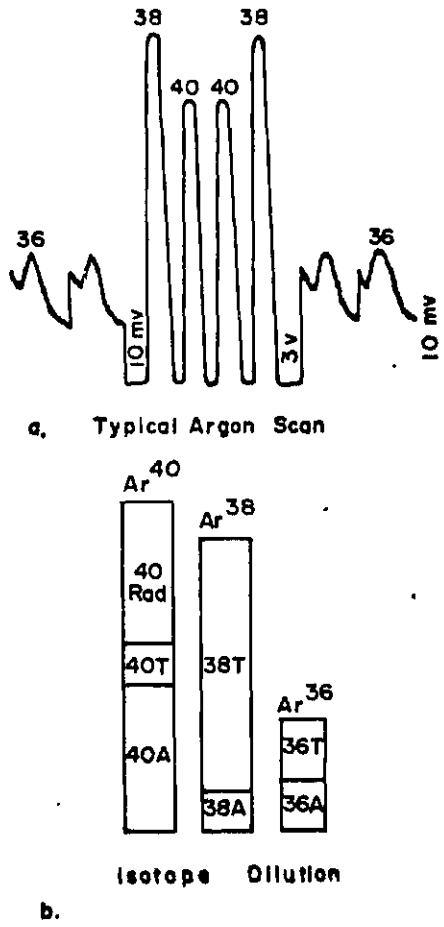


Figure 11. a. Typical Argon Scan. b. Diagrammatic Components of Argon in the Isotope Dilution Technique. (After Dalrymple and Lanphere, 1969).

Signals less than 30 mv are scanned twice and averaged. Each scan is repeated in reverse to produce a mirror image of the scan. The ion current ratio that the mass spectrometer provides is slightly different from the actual isotopic ratio, a phenomenon referred to as mass discrimination. The mass discrimination factor for the $^{36}Ar/^{40}Ar$ ratio is determined using atmospheric argon with a known $^{40}Ar/^{36}Ar$ ratio of 295.5. A correction for mass discrimination of the mass spectrometer must be applied to all isotopic ratios measured. The analytical precision of the mass spectrometer (MS 10) is less than 2% at the 95% confidence level.

In this study the stable isotope ^{38}Ar (99% pure) was used as an isotopic internal standard for quantitative determination of ^{40}Ar and ^{36}Ar by the stable isotope dilution technique. Dalrymple and Lanphere (1969) give specific equations for stable isotope dilution measurements in the K-Ar method in their Appendix D. The equation giving the (apparent) amount of radiogenic argon is:

$$^{40}Ar_{rad} = {}^{38}Ar_T \{(^{40}Ar/^{38}Ar)_M - (^{40}Ar/^{38}Ar)_T - \left[\frac{1 - (^{38}Ar/^{36}Ar)_M(^{36}Ar/^{38}Ar)_T}{(^{38}Ar/^{36}Ar)_M(^{36}Ar/^{38}Ar)_A - 1}\right]\left[(^{40}Ar/^{38}Ar)_A - (^{40}Ar/^{38}Ar)_M\right]\}, \quad (11)$$

where rad refers to radiogenic argon, A refers to atmospheric argon, T refers to the argon contributed by the isotopic internal standard (commonly called the tracer or spike), and M

refers to measured isotope ratio for the gas mixture. (The measured quantity $^{40}Ar_{rad}$ is actually the "apparent radiogenic argon" which is calculated from the analytical data and which may include extraneous ^{40}Ar which is not of atmospheric origin. The term radiogenic argon should be used to mean only the ^{40}Ar produced by the in situ decay of ^{40}K.) If the measured quantity, $^{40}Ar_{rad}$, is radiogenic argon (in this sense), then the calculated age is valid. To avoid confusion the term non-atmospheric argon may be used for the apparent radiogenic argon which is calculated from analytical data. Such non-atmospheric argon may include either radiogenic argon or extraneous argon or both.

The conventional potassium-argon age determination method, for which Equation 11 is applicable, assumes that only two components of argon are present in a sample to be dated--atmospheric argon and radiogenic argon, where the concept of radiogenic argon is restricted to that argon formed by radioactive decay within the sample since its formation. In many cases however, there is argon within samples which is neither of atmospheric origin nor of radiogenic (in the strict sense just mentioned) origin. Such argon is generally referred to as "extraneous" argon. Although atmospheric argon is also extraneous (See Chapter IV) the term extraneous argon is often used in the literature to mean only that portion of the extraneous argon which may not be attributed to (modern) atmospheric argon in a sample.

Operationally, the computation represented by Equation 11 divides the argon released from a sample into two categories-- atmospheric argon and non-atmospheric argon. The non-atmospheric argon may be entirely of radiogenic origin, or it may include some extraneous argon. In the following, the term "non-atmospheric argon" will be used when this (operationally defined) component of the argon in a sample must be explicitly identified. For convenience, the term "extraneous argon" will often be used to mean the portion of the non-atmospheric argon which is not radiogenic (when the context will make it clear that atmospheric argon is not included). Finally, where the presence of extraneous argon in the non-atmospheric component is conjectural, the term "apparent radiogenic argon" may be used for the non-atmospheric component.

Figure 11b diagramatically represents the distribution of argon isotopes in the various components of argon in an analysed gas sample for which the basic assumptions made in the convention K-Ar method hold. It is assumed that all ^{36}Ar measured except for the small amount contributed by the tracer is of atmospheric origin and that all non-atmospheric argon from the sample is radiogenic. These assumptions must be valid for the conventional K-Ar geochronological model to be correct. Thus the ^{40}Ar and ^{38}Ar contributed by the atmospheric component can be calculated, since the isotopic composition of atmospheric argon is known. The ^{38}Ar in excess of that in

the atmospheric component is the amount of ^{38}Ar contributed by the tracer. If the amount of $^{38}Ar_T$ is known, the amount of $^{40}Ar_{rad}$ can be computed.

For the system at Georgia Institute of Technology, School of Geophysical Sciences, a bulb reservoir is used for the tracer storage. The volume between the valves labeled S1 and S2 in Figure 10 constitutes the spike pipette. The volumes of the pipette and the resevoir have been determined gravimetrically. Each time a spike is used, the amount of spike in the reservoir is depleted, so a correction must be applied to the amount of tracer in each successive withdrawal. In each withdrawal, the reduction in amount may be expressed in terms of a depletion constant:

$$\delta = V_D/(V_D + V_E), \tag{12}$$

where V_D is equal to the volume of the spike pipette and V_E is the volume of the bulb reservoir. Since $V_D << V_E$, the amount of ^{38}Ar in a spike is given to a high degree of approximation by the equation:

$$^{38}Ar_T = T_o e^{-\delta x}, \tag{13}$$

where T_o is a constant and x is the tracer withdrawal number (Dalrymple and Lanphere, 1969). The constant T_o is obtained from the relationship:

$$T_o = {}^{38}Ar_T/e^{-\delta x}, \qquad (14)$$

where $^{38}Ar_T$ is experimentally determined in a calibration, which should be done several times.

Another bulb reservoir, containing a measured quantity of air, is used for calibration. An air argon pipette (between valves A1 and A2 in Figure 10) with a known volume is used to withdraw exact volumes from the measured volume in the air argon bulb reservoir. A known volume of air containing a known proportion of ^{40}Ar then can be spiked with $^{38}Ar_T$. Measurement of the $^{40}Ar/^{38}Ar$ ratio of the mixture provides an absolute value for $^{38}Ar_T$. This calibration based on air argon has not been completed on the system at Georgia Tech, so inter-laboratory reference samples which have been analysed by many laboratories which have completed the calibration, have been used as the basis for determining T_o.

After each analytical sample, a blank fusion is done in which the furnace is operated in the same way as in an actual sample run. This was found to be necessary because of the difficulty of baking all of the argon out of a viscous melt with a resistance heated furnace within a few minutes. A small correction for any radiogenic ^{40}Ar evolved in the blank fusion is applied to the previous run. The argon released in the blank fusion is measured in the same way as that from a sample fusion, but without a spike. Since the sensitivity of the mass spectrometer is approximately constant (within 20%) a false value for the ^{38}Ar signal may be used to compensate

for the absence of the spike, in the calculations.

Gases measured with a mass spectrometer operated in the static mode are contaminated by the previous sample because ions of the previous sample were driven into the walls and filament of the mass spectrometer. In subsequent runs the embedded gases slowly leak out and produce a "memory" effect. Farrar et al. (1964) suggested that the MS 10 does not have a memory effect. In the present study, a small memory effect has been observed in some of the blank runs, but the measured ratios were corrected for the "memory" effect. This is done by plotting $^{40}Ar/^{38}Ar$ and $^{38}Ar/^{36}Ar$ ratios versus time. The corrected ratios are found by extrapolating the observed ratios to the time when the sample was admitted to the mass spectrometer. The MS 10 measures isotopic ratios with an accuracy of $\pm$ 0.5% with proper calibration.

Whole Rock Chemical Analysis

Ten dolerite samples from ten dikes were analysed for major element content and TiO_2 using the $LiBO_2$ fusion technique with three analysed rock powders (USGS) as reference samples. In this technique, 0.7 g of $LiBO_2$ is placed in a graphite crucible. An aliquot of the whole rock material used for the K-Ar analysis was also used in the chemical analysis. A 0.10 g portion of the sample is weighed to 0.0001 g and poured into the graphite crucible containing the $LiBO_2$. The crucibles are placed in a furnace at 925°C for one-half

hour to fuse the sample with the $LiBo_2$. The molten sample is poured into a magnetically stirred 5% nitric acid solution accurately measured to 50 ml with a 50 ml pipette. After stirring, a second 50 ml of 5% nitric acid solution is added to the sample to bring the total volume up to 100 ml. The solution is filtered through a Whatman number 42 filter into 125 ml polypropylene bottles with caps. The same techniques were used on the USGS reference samples. The solutions were then analysed for major elements and TiO_2 using standard analytical procedures in atomic absorption spectrophotometry.

CHAPTER III

RESULTS

Petrographic Measurements

The major and accessory mineralogy were determined for one sample from each dike dated in this study. Table 2 is a tabulation of the minerals present in each rock sample. The estimated precision, based on counting 1200 points in the modal analysis, is better than 5% at the 95% confidence level. The value given for pyroxene includes all the different varieties which occur in each rock sample. The compositions of plagioclase, pyroxene, and olivine crystals were not determined in this study, as much work pertaining to mineralogical composition in the dolerite dikes of Georgia and the rest of the eastern United States was done by Weigand and Ragland (1970).

The appearance of secondary minerals (other than late stage crystallization products) such as chlorite, serpentine biotite, and sausserite in a dolerite indicates a rock which has not remained a closed system since crystallization. Significant argon loss occurs in the alteration of K-bearing minerals to secondary minerals provided the alteration occurred significantly later than the crystallization of the rock. If the secondary minerals contain K, then argon loss will

Table 2. Petrographic Modal Analyses of Selected Dolerite Dikes from Georgia (Values given in Percent of Total)

Sample	Plag.	Pyrox.	Qtz.	Micropeg.	Oliv.	Mag.	Il.	Chl.	Serp.	Saus.
Rabun County										
TRD 5	58	18	--	--	20	2	--	.3	1.2	.5
TRD 7	53	21	--	--	23	2.5	--	--	.5	--
TRD 25	50	17	--	--	24	2.5	.5	--	1.0	5.2
Dekalb County										
D 9	48	47	--	--	--	4.0	--	.33	.33	.33
Gwinnett County										
G 1	61	25	--	--	12	2.0	--	--	--	--
G 8	64	17	--	--	7	6.0	.06	.14	2.5	3.3
Bibb County										
Bi 4	54	30	--	--	8.7	1.3	--	--	6.0	--
Jackson-Hall County										
JH 3	62	12.2	--	--	10.6	3.6	--	--	3.6	8.0
Greene County										
Gr 7	58	26	--	--	14	1.5	--	.5	--	--
Rockdale County										
R 9	43.8	42.8	--	.2	--	2.3	.1	--	.4	9.8
R 18	34	48	--	.2	--	3.0	--	--	.15	14.0
Newton County										
N 3	44	35	--	--	--	3.0	.4	1.0	--	5.4

Table 2 Continued.

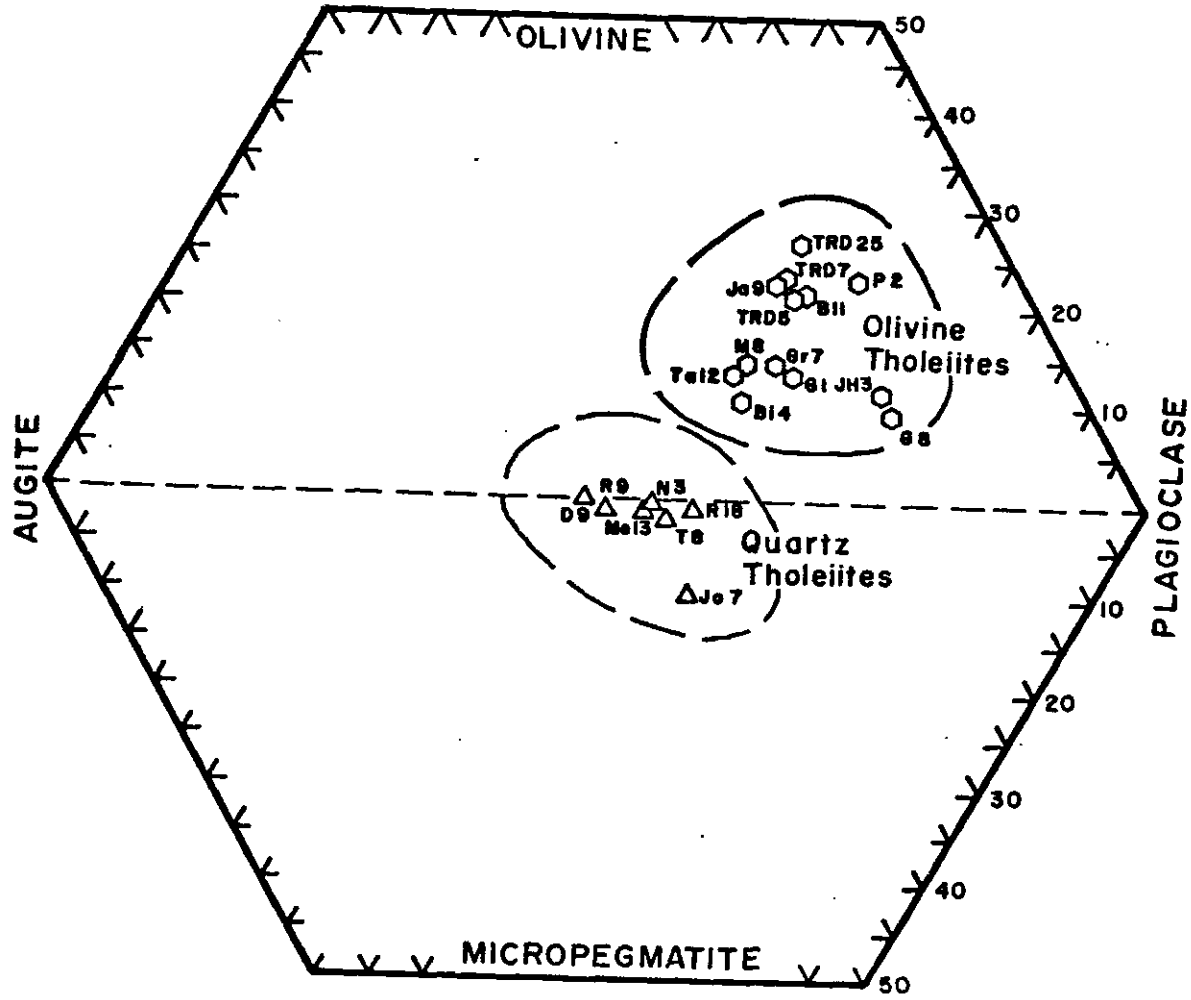
Sample	Plag.	Pyrox.	Qtz.	Micropeg.	Oliv.	Mag.	Il.	Chl.	Serp.	Saus.
Putnam County										
P 2	59	14	--	--	22	3	--	--	1.6	.4
Jasper County										
Ja 9	52	22	--	--	20	2.6	--	--	4.4	--
Meriwether County										
Me 13	49	45	.1	1.8	--	3.5	--	--	--	--
Talbot County										
T 8	51	40	--	1.5	.1	1.5	.5	.5	.5	4.3
Jones County										
Jo 7	47	33	--	8.4	--	3.4	.2	--	1.4	5.4
Monroe County										
M 8	55	30	--	--	13	2.5	--	--	4.4	--
Taliaferro County										
Ta 12	54	30	--	--	13	2.3	--	--	--	.9
Barrow County										
B 11	55	20	--	--	20	4.0	--	--	.7	.3

affect the K-Ar apparent age. It can be seen in Table 2 that most samples dated in this study contain secondary minerals. Generally, small amounts of secondary mineralization can be ignored, but it should be pointed out that some of the samples dated have a significant amount of secondary mineralization. Therefore the dates from those should be suspect. Samples M8, Jo7, T8, Ja9, N3, R18, R9, JH3, G8, Bi4, and TRD25 are in this category.

The presence of micropegmatite (intergrowths of quartz and K feldspar, interstitially) might cause a rock system to lose radiogenic argon. The amount of argon loss has not been documented for hypabyssal K feldspar, but it has been clearly documented that plutonic K feldspar loses radiogenic argon during exsolution (formation of perthites). Increasing degree of perthitization is associated with increasing loss of radiogenic argon (Sardarov, 1957). Samples Jo7, T8, Mel3, R9, and R18 contain micropegmatite and may have suffered radiogenic argon loss. In rocks with low K contents (such as dolerites; 0.2-0.7% K by weight) a small amount of a K rich mineral phase would contribute a significant fraction of the total radiogenic argon, and hence the proportion of radiogenic argon loss due to exsolution of a K feldspar mineral phase would be further enhanced. Furthermore the pyroxenes in tholeiites exsolve into 001 and 100 lamellae after crystallization, forming a characteristic herringbone structure. There has been little or no work done on pyroxenes re-

garding exsolution and radiogenic argon loss. It is suggested that the mechanism by which radiogenic argon is lost during exsolution of K feldspars might be similar in the pyroxenes. Further work in this area would be useful in evaluation of diffusion of argon in minerals which undergo solid state structural transformations after crystallization at moderate temperatures.

Figure 12 is a plot of modal mineralogy for the dolerites dated in this study. Weigand and Ragland (1970) have characterized the chemistry of the dolerites in eastern North America. Their data suggest that three main groups of dolerites exist; the olivine normative tholeiite, the low TiO_2 quartz normative tholeiite, and the high TiO_2 quartz normative tholeiite. These subdivisions were based on calculating the norms from complete chemical analyses. The plot of modal mineralogy cannot distinguish among the three groups, but it does show two groupings which correspond to the subdivision between olivine and quartz tholeiites. The samples which show olivine present in greater than a few percent can definitely be placed in the olivine tholeiite classification. The samples which have little or no olivine and small amounts of micropegmatite present can be placed in the group of quartz tholeiites. The normative mineralogy has not been calculated in this study. The reader is referred to Weigand and Ragland (1970) and Smith et al. (1975) for normative mineralogy which is characteristic of the dolerites in eastern



MODAL MINERALOGY OF THE
DOLERITE DIKES OF GA.

Figure 12. Modal Mineralogy of Selected Georgia Dolerites.

North America. Also the compositions of the various mineral phases present in the dolerites were determined in these works.

Brief petrographic descriptions of each chemical group of tholeiites will be given here. A detailed petrographic description of each dated sample appears in the Appendix. A chilled margin sample of olivine tholeiitic composition is typically an aphanitic, holocrystalline, melanocratic dolerite. The texture of an olivine tholeiite ranges from ophitic to subophitic. Coarser grained varieties of the olivine tholeiite occur in most dikes toward their centers. The olivine tholeiite contains the essential minerals olivine (5-30% by volume), plagioclase (50-65% by volume) and pyroxene (10-30% by volume). The olivine crystals occur as phenocrysts in some chilled margins, and are in contact with plagioclase and pyroxene. The plagioclase laths generally do not penetrate the olivine crystals. Plagioclase laths form spherulites which are generally randomly distributed throughout the rock. Pyroxene occurs in large, optically continuous patches. The plagioclase laths do penetrate the pyroxene crystals (usually augite) and are in contact with olivine and pyroxene. The accessory minerals magnetite, ilmenite, and apatite are generally present in small amounts for most dolerites. Secondary minerals such as serpentine replacing olivine, biotite replacing pyroxene, sausserite replacing plagi-

oclase, and chlorite replacing pyroxene and biotite occur in varying degree from sample to sample. Smith et al. (1975) noted the presence of the sulfides, pyrrhotite and pentlandite which occur as finely disseminated crystals, in dolerites from Pennsylvania.

The low TiO_2 quartz tholeiite from a chilled margin sample is an aphanitic, holocrystalline, microporphyritic, idiomorphic granular, melanocratic dolerite. Its texture can range from intergranular to subophitic in some cases. It is composed of the essential minerals plagioclase and pyroxene. Euhedral plagioclase laths comprise about 50% of the rock and fill its groundmass. Plagioclase phenocrysts are common in most samples. The polysynthetically twinned plagioclase crystals in the ground mass occur as spherulites. The microphenocrysts of plagioclase do not form radiating blades but occur as individual crystallites, randomly oriented. The plagioclase laths do not penetrate the pyroxene crystals. Pyroxenes, augite and hypersthene or pigeonite, occur interstitially and in the ground mass in randomly oriented subhedral to anhedral crystals. The accessory minerals olivine (only in trace amounts), apatite, and magnetite occur in small quantities. Pyrrhotite and chalcopyrite are the main sulfide phases observed in the low TiO_2 quartz tholeiites by Smith et al. (1975). The secondary minerals iddingsite (reaction rim around olivine), sausserite, chlorite, biotite, and serpentine occur in varying amounts.

The high TiO_2 quartz tholeiite from a chilled margin sample is an aphanitic, holocrystalline, melanocratic dolerite with a texture which varies from intergranular to subophitic to idiomorphic-granular. The essential mineralogy consists of plagioclase (about 50% by volume) and the pyroxenes (augite and hypersthene or pigeonite)(about 35% by volume). Euhedral polysynthetically twinned plagioclase laths occur in two distinct sizes. The larger crystals (3-5 mm in length) are phenocrysts. The smaller ones occur in the ground mass,and only the centers of spherulites are preserved. Euhedral to subhedral pyroxene crystals occur parallel to the plagioclase laths and are not penetrated by the plagioclase. Pyroxene is seen to replace plagioclase, in places where one-half of an apparently twinned crystal is pyroxene and the other half plagioclase. Accessory minerals micropegmatite (triangular intergrowths of quartz and K feldspar), apatite, ilmenite and magnetite occur in amounts usually less than 1% of the total rock. The micropegmatite is generally in contact only with plagioclase. Euhedral magnetite crystals occur replacing plagioclase and pyroxene and is in contact with both crystals. Magnetite occurs as individual cubic and tetrahedral crystals but in many places interlock to form larger patches. Ilmenite occurs as large dendritic or skeletal crystals and is usually identified by its bifurcating crystal habit.

One other type of quartz tholeiite is found in the

Georgia dolerite dikes. The high TiO_2, high Fe_2O_3, quartz tholeiite is essentially the same petrographically as the high TiO_2 quartz tholeiite. A description of the petrography for this dolerite will be foregone in light of the previous description. The essential difference between the high TiO_2 quartz tholeiite and the high TiO_2, high Fe_2O_3, quartz tholeiite is in the amount of iron oxides present in the sample. Large patches of ilmenite intergrown with magnetite may account for the unusually high Fe_2O_3 content. Weigand and Ragland (1970) suggest that local contamination is responsible for the higher iron oxide content of the high TiO_2, high Fe_2O_3, quartz tholeiite.

Detailed petrographic knowledge of each sample dated (in the Appendix) is important in evaluating the meaning of any K-Ar data obtained. Knowledge of secondary minerals and their times of formation, as well as of materials which may have poor retentivity for radiogenic argon, will aid in determining the validity of K-Ar geochronological data.

Conventional K-Ar Analyses

Table 3 is a compilation of K content, $^{40}Ar_{rad}$ content (given as percent of total argon and as standard nanoliters/gm), apparent age (two columns representing ages calculated on the basis of the old and new decay constants), and chemical class for the whole-rock samples of dolerite dikes dated in this study. These samples are listed under the respective

Table 3. K-Ar Results for Whole Rock Dolerite Samples

Sample	K(% by weight)	Non-atmospheric* ^{40}Ar (% of total Argon)	Non-atmospheric* ^{40}Ar nl/g	[a]Apparent Age (m.y.)	[b]Apparent Age (m.y.)	Chemical Group
Rabun County						
TRD5-1C	.429	91.3	16.37	774±15	785±16	Olivine Tholeiite
TRD6-1CII	.255	88.9	11.65	894±18	906±17	Olivine Tholeiite
TRD7-1CII	.483	94.0	13.22	585±12	595±13	Olivine Tholeiite
TRD8-1CII	.405	91.0	13.28	682±13	693±14	Olivine Tholeiite
TRD12-1C	.428	94.7	38.91	1494±30	1505±31	Olivine Tholeiite
TRD16-1CII	.473	45.6	15.97	699±14	710±15	Olivine Tholeiite
duplicate		91.3	15.29	674±13	685±14	Olivine Tholeiite
TRD25-1C	.471	95.7	12.58	573±11	584±12	Olivine Tholeiite
TRD27-1C	.365	80.6	7.86	475± 9	484±10	Olivine Tholeiite
TRD28-1C	.368	75.3	9.73	568±11	577±12	Olivine Tholeiite
Dekalb County						
D5-1C	.412	68.8	4.84	274± 5	281± 5	Quartz Tholeiite
duplicate		82.0	5.01	282± 6	286± 6	Quartz Tholeiite
D6-1C	.387	58.3	3.98	242± 5	248± 5	Quartz Tholeiite
D9-1C	.371	65.2	3.96	250± 5	256± 5	Quartz "

*The quantity determined using Equation 11 is here called "non-atmospheric" ^{40}Ar rather than $^{40}Ar_{rad}$, since many of these samples clearly have excess ^{40}Ar as well as radiogenic argon formed by the *in situ* decay of ^{40}K within rocks.

[a]Based on the old constants: $\lambda_\varepsilon = 0.585 \times 10^{-10} y^{-1}$, $\lambda_\beta = 4.72 \times 10^{-10} y^{-1}$, $^{40}K/K_{total} = 0.000119$.

[b]Based on the new constants: $\lambda_\varepsilon = 0.575 \times 10^{-10} y^{-1}$, $\lambda_\beta = 4.905 \times 10^{-10} y^{-1}$, $^{40}K/K_{total} = 0.000118$.

Table 3 Continued.

Sample	K(% by weight)	Non-atmospheric* ^{40}Ar (% of total Argon)	Non-atmospheric* ^{40}Ar nl/g	[a]Apparent Age (m.y.)	[b]Apparent Age (m.y.)	Chemical Group
Gwinnett County						
G2-1C	.456	85.7	3.54	185± 4	189± 4	Olivine Tholeiite
G3-1C	.474	88.1	4.08	204± 4	209± 4	Olivine Tholeiite
duplicate		87.0	4.15	208± 4	213± 4	Olivine Tholeiite
G8-1C	.175	62.5	2.19	290± 6	296± 6	Olivine Tholeiite
duplicate		64.3	2.26	299± 6	306± 6	Olivine Tholeiite
Bibb County						
Bi4-1CII	.154	54.8	1.35	209± 4	214± 4	Olivine Tholeiite
duplicate		24.6	1.26	195± 8	199± 8	Olivine Tholeiite
Jackson-Hall County						
JH3-1C	.230	61.9	4.32	420± 8	428± 8	Olivine Tholeiite
duplicate		69.5	4.39	427± 8	434± 8	Olivine Tholeiite
Clarke County						
C3-1CII	.250	95.3	25.27	1652±33	1659±33	Olivine Tholeiite
duplicate		95.0	25.54	1617±32	1625±32	Olivine Tholeiite
Greene County						
Gr7-1CII	.109	55.8	1.05	227± 5	230± 5	Olivine Tholeiite

Table 3 Continued.

Sample	K(% by weight)	Non-atmospheric* ^{40}Ar (% of total Argon)	Non-atmospheric* ^{40}Ar nl/g	[a]Apparent Age (m.y.)	[b]Apparent Age (m.y.)	Chemical Group
Rockdale County						
R9-1CII	.469	77.2	3.73	190± 4	194± 4	Quartz Tholeiite
duplicate		61.8	3.73	190± 4	194± 4	Quartz Tholeiite
R18-1CII	.512	83.8	5.43	249± 5	256± 5	Quartz Tholeiite
duplicate		75.7	5.30	243± 5	250± 5	Quartz Tholeiite
Newton County						
N3-1CII	.656	85.9	5.25	191± 4	194± 4	Quartz Tholeiite
Putnam County						
P2-1CII	.204	75.6	2.12	244± 5	250± 5	Olivine Tholeiite
Jasper County						
Ja9-1CII	.214	45.4	2.07	228± 5	234± 5	Olivine Tholeiite
Meriwether County						
Mel3-1CIII	.369	85.0	2.88	187± 4	190± 4	Quartz Tholeiite
duplicate		88.6	2.98	192± 4	195± 4	Quartz Tholeiite
Talbot County						
T8-1CII	.438	83.5	4.16	225± 5	230± 5	Quartz Tholeiite
duplicate		88.2	4.05	218± 5	223± 5	Quartz Tholeiite

Table 3 continued.

Sample	K(% by weight)	Non-Atmospheric* ^{40}Ar (% of total Argon)	Non-Atmospheric* ^{40}Ar nl/g	[a]Apparent Age (m.y.)	[b]Apparent Age (m.y.)	Chemical Group
Jones County						
Jo7-1CII	.519	82.5	4.09	188± 4	190± 4	Quartz Tholeiite
Monroe County						
M8-1C	.283	75.0	2.67	223± 5	230± 5	Olivine Tholeiite
duplicate		71.4	2.72	227± 5	231± 5	Olivine Tholeiite
Taliaferro County						
Tal2-1C	.187	74.1	1.49	191± 4	194± 4	Olivine Tholeiite
duplicate		66.4	1.45	186± 4	189± 4	Olivine Tholeiite
triplicate		47.0	1.45	186± 4	189± 4	Olivine Tholeiite
Barrow County						
B11-1C	.387	90.9	8.86	501±10	509±10	Olivine Tholeiite
duplicate		88.6	8.82	499±10	508±10	Olivine Tholeiite
Pulaski County						
GGS 4780	.239	16.7	1.80	180±18	184±18	not available
GGS 4820	.208	8.7	1.07	125±12	128±12	not available
GGS 4850	.299	15.6	2.62	200±14	204±14	not available
(These samples are from GGS Well number 3137)						

counties from which they were taken. Actual sample localities for each specimen for which thin sections were made appears in the Appendix. Figure 13 shows the distribution of the chemical types and apparent K-Ar ages of the dikes on a map of Georgia. It should be noted that three samples were cuttings from a sill under the Coastal Plain in Pulaski County, taken from well number GGS 3137. (The samples were obtained by Dr. Lynn Pollard from the Georgia Geological Survey). The K value given in Table 3 is the average value of duplicate analyses with an analytical precision of 1% at the 95% confidence level. The argon values are given for each portion of a sample which was successfully analysed for argon. The estimated precision of the values for radiogenic argon content is 2% at the 95% confidence level.

Four mineral separates were analysed to provide information about the amount and isotopic composition of argon in the different mineral phases of dolerites (Table 4). Three samples of quartz and a couple of other samples from the country rock near dikes were analysed to obtain information about argon present in the rocks during the intrusion of the dikes. In an earlier study, one biotite sample from the contact of a dike had been analysed to give an estimate on the time of intrusion of the dike. These results are also listed in Table 4. More work of this type is needed to provide a more positive interpretation of the K-Ar apparent ages.

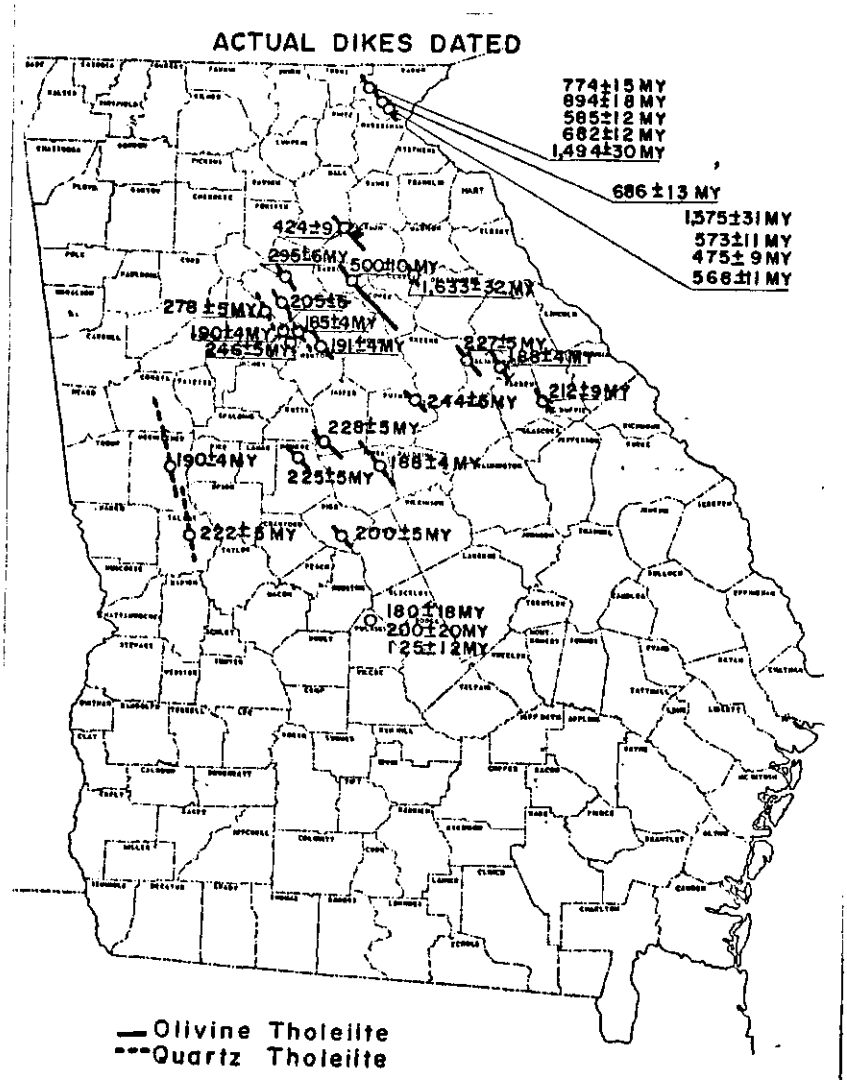


Figure 13. Actual Dikes Dated in this Study presented on a base map of Georgia.

Table 4. K-Ar Results of Country Rocks, Mineral Separates, and Standards

Sample	K(% by weight)	Non-atmospheric* ^{40}Ar (% of total Argon)	Non-atmospheric* ^{40}Ar nl/g	[a] Apparent† Age (m.y.)	[b] Apparent† Age (m.y.)	Material
Rabun County						
TRD2A-1CR	.137	66.6	2.32	384± 8	392± 8	Amphibolite
TRD1A-1CR	.128	61.3	2.30	404± 8	413± 8	Amphibolite
WRG-1HH	.246	95.6	2.88	275± 5	281± 5	Hornblende Separate
TRD6-2H	.115	89.0	7.14	1138±23	1149±24	Pyroxene Separate
TRD6-2F	.396	79.8	15.40	786±16	797±24	Plagioclase Separate
TRD24A-2H	.170	82.6	5.01	634±12	644±13	Pyroxene Separate
TRD24A-2F	.553	92.2	17.71	672±13	683±14	Plagioclase Separate
TRD20-CR	.036	76.2	.70	n/a	n/a	Quartz in contact
TRD10-CR	.048	63.9	1.01	n/a	n/a	Quartz in contact
TRD21-CR	.013	26.3	8.32	n/a	n/a	Quartz in contact
Warren County						
JWS-B	6.860	92.1	61.30	212± 7	215± 7	Biotite from rock in contact with dike from Camak Quarry
Standards						
LP-6	8.332	93.6	42.41	123± 2	128± 2	Biotite standard
duplicate	8.332	97.1	43.37	126± 2	129± 2	Biotite standard
AVSL	3.366	95.8	41.26	285± 6	292± 6	Slate standard
duplicate	3.366	98.8	41.63	287± 6	293± 6	Slate standard

*Refer to Table 3 for explanation of the term "non-atmospheric" ^{40}Ar

†Decay constants and K abundances for columns a and b are the same as in Table 3.

n/a means not applicable

Figure 14 is an histogram of K-Ar apparent ages for the dolerite dikes of the Georgia Piedmont and Blue Ridge Mountain district analysed in this study. A peak is seen at 190 to 210 m.y., consistent with the time most commonly suggested for continental rifting to have begun. (The K-Ar apparent ages used here and in the following discussions and graphs are based on the older decay constants which appear in Table 3.) Many samples produced apparent ages greater than 190-210 m.y. The frequency of older apparent ages decreases with increasing apparent age, and produces a distribution of approximate exponential appearance. This result is remarkably similar to the results of Dalrymple et al., (1975) in their study of Liberian dikes (Figure 15). If one is willing to accept that the time of crystallization of the dolerite dikes in Georgia is limited to a 70 m.y. time interval beginning 230 m.y. ago and ending 160 m.y. ago (See Chapter I), then it can be seen that many samples dated in this study produce apparent ages greater than their geologic age.

Analyses of Multiple Whole Rock Samples

Figure 16 shows detailed sampling of each dike for which multiple whole rock samples have been analysed. Two of the dikes are from Rabun County, a third dike is from Stone Mountain in Dekalb County, a fourth dike is from Gwinnett County, and a fifth dike is from Rockdale County.

The two dikes in Rabun County gave apparent age ranges

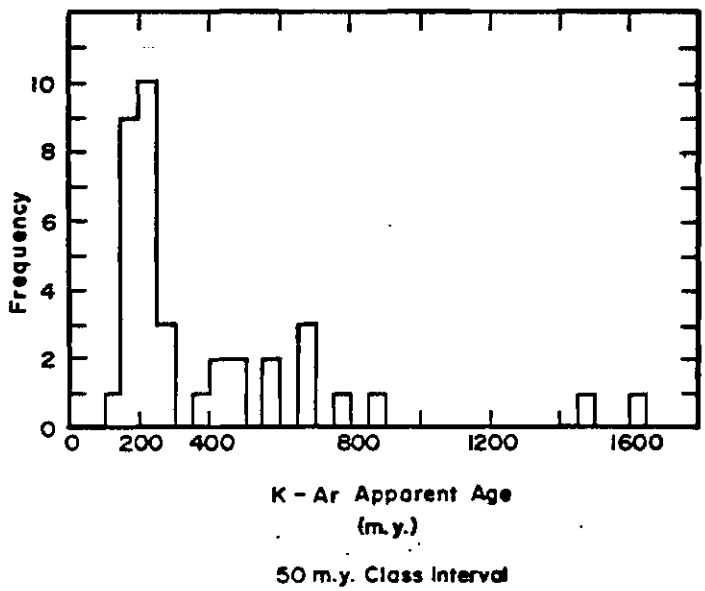
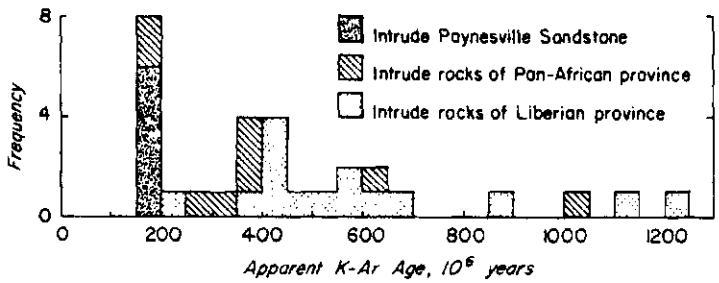


Figure 14. Frequency of K-Ar Apparent Ages for Georgia Dolerites.



Histogram of K-Ar ages on Liberian diabase dikes and sills. Class interval is 50 m.y.

Figure 15. Frequency of K-Ar Apparent Ages and Correlation to Rock Type Intruded for Liberian Dolerites. (After Dalrymple et al., 1975).

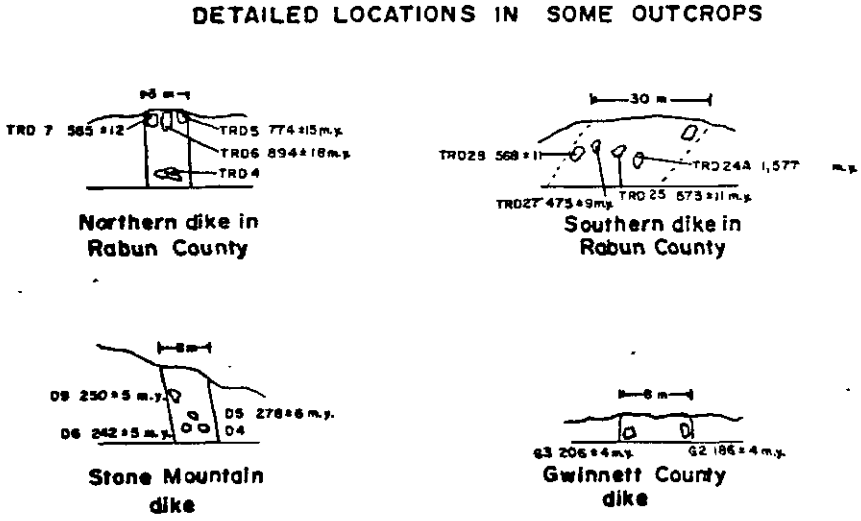


Figure 16. Sample Locations for Selected Dolerite Dikes (Detailed).

from 585 ± 12 m.y. to 1,494 ± 30 m.y. and from 475 ± 9 m.y. to 1577 ± 31 m.y. The Stone Mountain dike gave apparent ages ranging from 242 ± 5 m.y. to 282 ± 6 m.y. The dike in Gwinnett County produced a range in apparent ages of 185 ± 4 m.y. to 205 ± 4 m.y. Only two samples of the Rockdale County dike were analysed and apparent ages of 190 ± 4 m.y. and 247 ± 5 m.y. were obtained. The ages reported here are averaged from the values (using old constants) given in Table 3.

Figure 17 is a plot of K-Ar apparent age (m.y.) versus K in weight percent for whole-rock samples from four of these dikes. The solid line connects samples from the Gwinnett County dike and suggests that the apparent age is a inverse function of the K content. The top part of Figure 17 shows the results from the two dikes studied in Rabun County. The top curve (long-dashed line) in Figure 17 shows the same relationship of increasing apparent age with decreasing K content. The short-dashed line (the other Rabun County dike) shows the same relationship although not as convincingly because of more scatter of the data. The samples labeled D5, D6, and D9 are from the Stone Mountain dike (dotted line) but do not exhibit a large enough range in K content to show any significant relationship.

Analyses of Separated Mineral Samples

The mineral separates analysed in this study were from the Rabun County dikes. Two light fractions composed of pla-

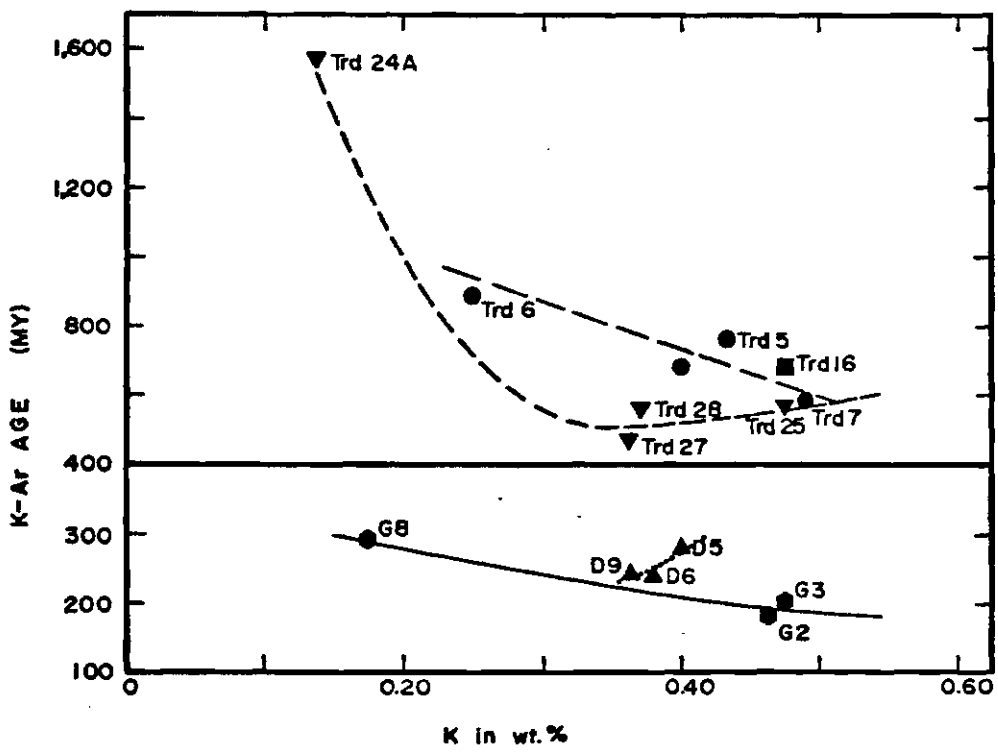


Figure 17. K-Ar Apparent Age Versus K (in Weight Percent).

gioclase (about 95% pure) and two heavy fractions composed of olivine and pyroxene were analysed. Magnetite had been removed with a magnet. Mineral separates are ideal to show whether the ratio of potassium to non-atmospheric argon varies from mineral to mineral and thus whether the system contains excess ^{40}Ar. Dalrymple et al. (1975) analysed the plagioclase fraction of dolerites which intruded the Paleozoic sandstones in Liberia. He obtained reliable K-Ar apparent ages near 170 m.y. The results of Dalrymple et al. were based only on the plagioclase fractions; there was no direct comparison between the various mineral phases of a single dolerite sample. In this study, apparent ages of 1,138 ± 23 m.y. and 786 ± 16 m.y. were obtained for the mineral separates TRD6-2H (pyroxene-olivine fraction) and TRD6-2F (feldspar fraction) respectively (Table 4). The more K deficient phase (pyroxene-olivine fraction) shows an older date, presumably because excess ^{40}Ar is relatively more abundant in this fraction. The plagioclase fraction appears to have incorporated more excess ^{40}Ar than the heavy fraction (as Dalrymple et al. also observed). Samples TRD24A-2H (pyroxene-olivine fraction) and TRD24A-2F yielded K-Ar apparent ages of 634 ± 12 m.y. and 672 ± 13 m.y. respectively. Again the plagioclase has more extraneous argon than the pyroxene-olivine fraction, although the apparent ages are, fortuitously, not very different.

The three quartz samples, TRD20-Cr, TRD21-Cr, and

TRD10-Cr, were difficult to fuse in the resistance heated furnace and complete fusion was not accomplished, so the values for non-atmospheric ^{40}Ar must be regarded as minimum amounts. The data show that significant amounts of non-atmospheric ^{40}Ar was incorporated in quartz samples in contact with the Rabun County dikes. This is evidence for the existence of non-atmospheric ^{40}Ar in the environment in which the dolerites crystallized. Rock samples and a separated hornblende from the vicinity of the Rabun County dikes but far enough away to be beyond their thermal influence, produced Paleozoic apparent ages, which suggests that regional metamorphism in this area ended in the Paleozoic Era (a result consistent with the patterns of K-Ar age relationships for the metamorphic rocks in Georgia.) This conclusively proves that the Rabun County dikes (which were formed after regional metamorphism ended) give anomalously old K-Ar apparent ages. Thus the K-Ar ages obtained must be regarded as invalid.

Figure 18 shows the distribution of Georgia dikes for which K-Ar apparent ages have been obtained in this study. The dotted line separates most of the dikes which show unreasonably high apparent ages from dikes which yield apparent ages which fall within the upper and lower acceptable age limits. The dikes to the northwest of the dotted line are definite cases of samples which contain variable amounts of ^{40}Ar which is neither of atmospheric origin nor formed <u>in situ</u>

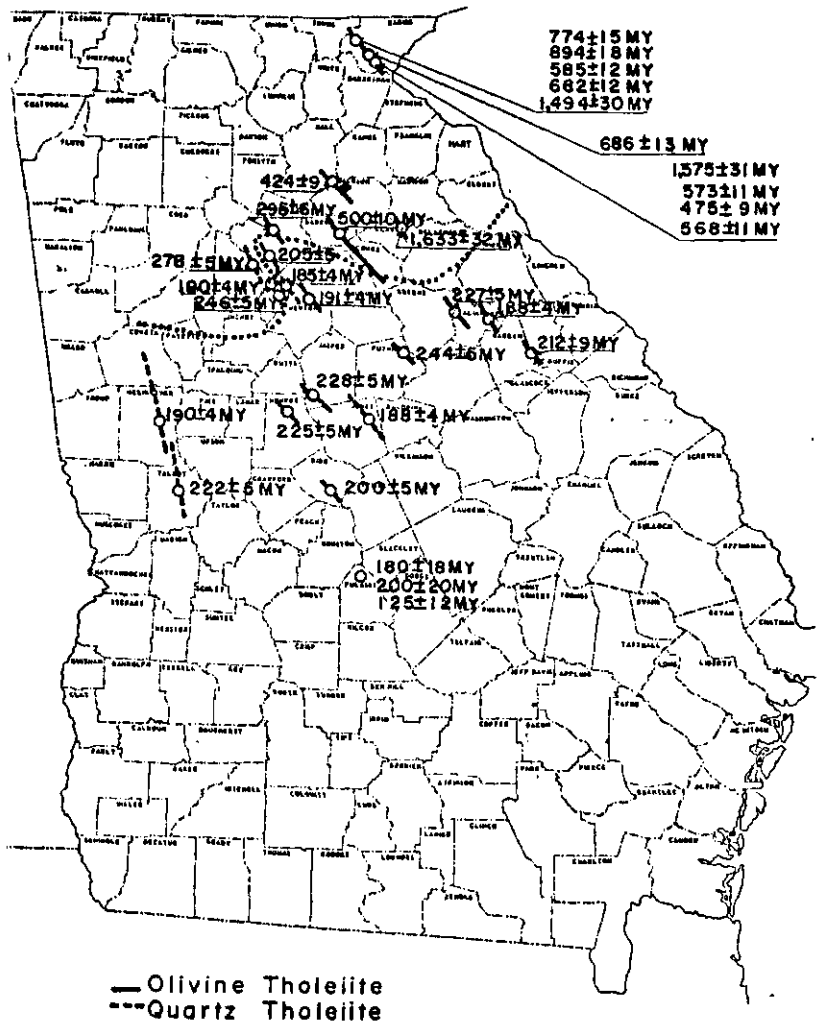


Figure 18. Dotted Line Divides Dolerites with Anomalously old Apparent Ages and those with Reasonable Apparent Ages.

within the rocks by decay of ^{40}K. Samples Ja9, R9, N3, Jo7, G3, Tal2, Mel3, Bi4, and T8, to the southeast of the dotted line, have apparent ages within the acceptable age limits. These samples are the only ones which should be used to show if correlations between age and chemistry or strike of the dikes exist.

Low Temperature Release of Non-Atmospheric Argon

Two Georgian dolerite samples were studied along with a series of dolerites from Virginia. The Virginian dolerites released only atmospheric ^{40}Ar at low temperatures up to 400°C. The two samples from Rabun County, Georgia, which were analysed at low temperatures, produced anomalously old K-Ar apparent ages. The Georgian samples released non-atmospheric argon at low temperatures. The atmospheric argon component of the argon released from these samples decreased with increasing temperature up to 300°C. The amount of the non-atmospheric component generally increased with temperature, but one sample showed a pulse of non-atmospheric argon released at 200°C. These results can be seen in Figure 19.

The argon which is released from dolerites at low temperatures has been usually thought to be atmospheric argon. These experiments show that some non-atmospheric ^{40}Ar is released at low temperatures for dolerites which produce anomalously old ages. This non-atmospheric ^{40}Ar is suggested to be initial argon which was somehow trapped between the grains

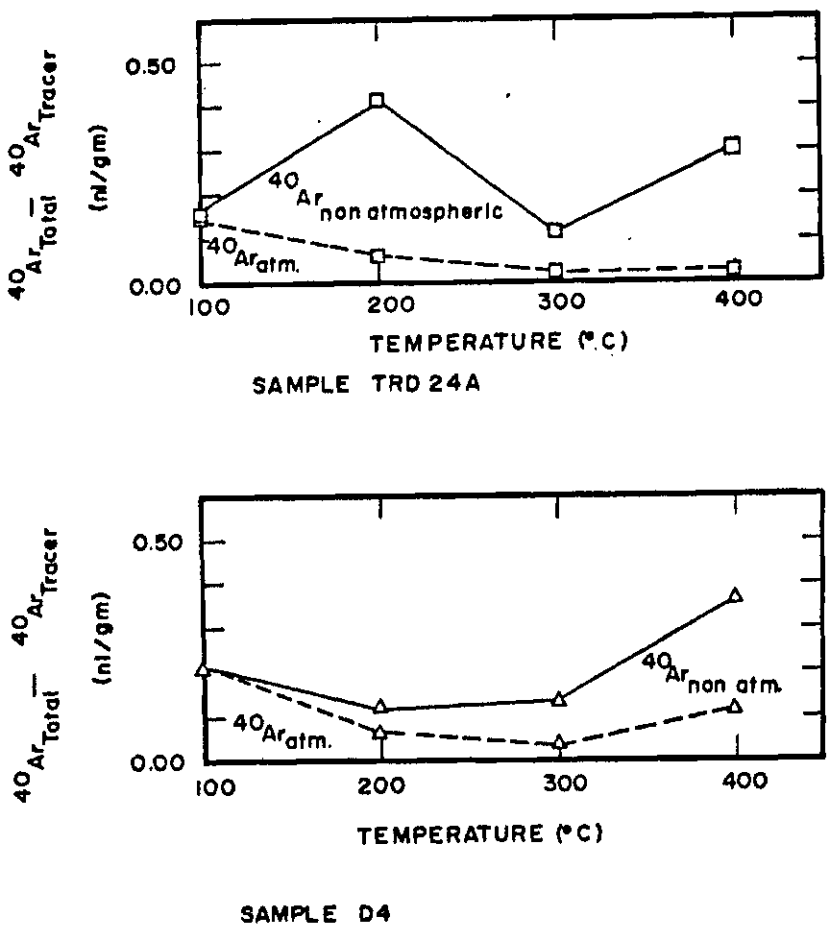


Figure 19. Low Temperature Release of Non-atmospheric Argon for Two Dolerites from Georgia.

or diffused into intergranular spaces during cooling. A small fraction of the initial argon is trapped in this way. The rest is dissolved in the various mineral phases and is released at the same temperatures that radiogenic argon is released. Thus, the low temperature release of non-atmospheric ^{40}Ar may be a useful criterion for identifying dolerites which contain initial argon.

Clearly, the K-Ar data can be shown to be a result of an initially complex open system with respect to argon isotopes. Some dikes may have initial radiogenic argon, but may subsequently have lost radiogenic argon to produce fortuitously reasonable ages. Such systems do not fulfill all the basic assumptions made in the conventional K-Ar dating method, so valid ages cannot be obtained. Cases of excess ^{40}Ar and diffusional loss of radiogenic argon exist for some of the dikes dated in this study. Careful evaluation of the validity of K-Ar apparent ages must be made for each dike, on an individual basis, before the age can be accepted as representing the true age of a tectonic event.

Major Element Abundances in Selected Dolerite Dikes

Table 5 is a tabulation of the major elements in terms of oxides given in weight percent. The samples analysed were the ones which yielded reasonable K-Ar apparent ages. The estimated analytical precision of the chemical analyses is 5% at the 95% confidence level. Iron is reported as Fe_2O_3* (FeO

Table 5. Major Element Abundances of Selected Dolerites of Georgia

Sample	SiO_2	Al_2O_3	Fe_2O_3*	CaO	MgO	K_2O	Na_2O	TiO_2	Total
G8-1C	46.1	17.6	14.4	10.3	7.7	.20	2.62	1.16	100.08
Bi4-1C	50.4	12.4	16.5	9.9	6.9	.52	2.13	1.29	103.90
R9-1C	54.4	16.0	12.0	12.4	7.9	.57	2.03	.76	106.07
R9-1F†	52.6	17.1	10.5	10.0	6.0	.54	2.15	.60	99.52
N3-1C	53.5	15.3	12.4	10.3	6.9	.77	2.16	.79	102.09
Ja9-1C	49.2	16.9	12.6	10.8	10.0	.26	1.87	.62	102.09
Mel3-1C	53.2	15.0	15.6	21.8	7.0	.45	2.25	1.26	116.55
Mel3-1F†	52.7	17.3	12.5	11.7	5.2	.41	2.56	1.04	103.42
T8-1C	53.2	12.4	16.5	10.0	6.9	.52	2.13	1.29	102.95
Jo7-1C	53.9	15.4	12.7	9.9	7.1	.64	2.18	1.02	102.84
Tal2-1C	49.0	18.5	15.1	9.6	8.3	.20	2.69	1.16	104.49

Chemical Analyses done using the $LiBO_2$ Fusion Technique (Values given in % by weight)

†Fine Fraction (less than 0.05 mm) decanted from analytical sample

*Total iron as Fe_2O_3

+ Fe_2O_3 reported as Fe_2O_3). Since, after crushing, the fine fraction had been removed from each analytical sample, the fine fraction was chemically analysed for two samples. The chemical composition of each of these fine fraction differs only slightly from that of the main sample, so it is concluded that removal of the fine fractions has had an insignificant effect on the results of the major element analyses.

Figure 20 is a plot of mafic index (Fe_2O_3*/Fe_2O_3* + MgO) versus TiO_2 in weight percent, for the quartz tholeiites. The data are encircled by dotted lines and show ranges not too much different from the ranges for the three chemical classes of quartz tholeiites obtained by Weigand and Ragland (1970). All three types of quartz tholeiites (low-Ti quartz tholeiite, high-Ti quartz tholeiite, and high-Ti-high Fe_2O_3 quartz tholeiite) exist in Georgia. Weigand and Ragland (1970) found only olivine tholeiites and low-Ti quartz tholeiites in Georgia, but their sampling of the dikes in Georgia was much less complete than in this study.

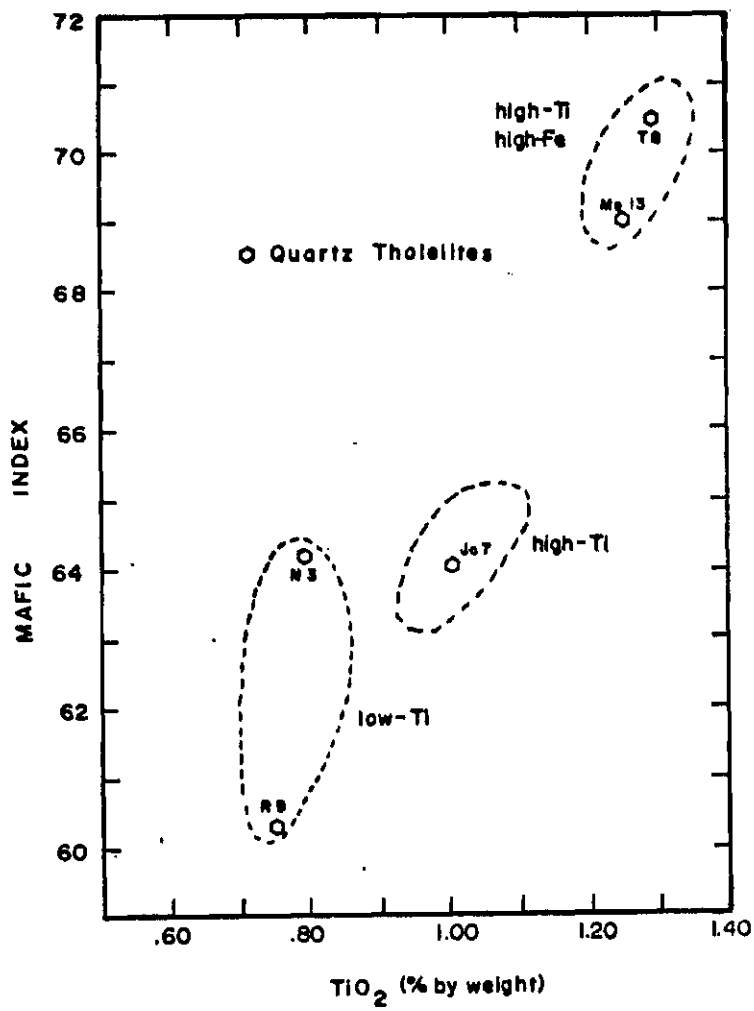


Figure 20. Mafic Index Versus TiO_2 (in weight percent) for Selected Georgia Dolerites.

CHAPTER IV

VALIDITY OF K-Ar AGES

The Extraneous Argon Problem

Extraneous argon can originate in several ways. Therefore it is necessary to develop a terminology which encompasses all possible origins of extraneous ^{40}Ar. The terminology of Damon (1970) has been adopted for this work, with slight modification. Damon recognizes three major components of ^{40}Ar: environmental ^{40}Ar, radiogenic ^{40}Ar, and extraneous ^{40}Ar. The radiogenic ^{40}Ar component has already been explained. Environmental ^{40}Ar is external argon partial pressure with reference to a rock or mineral. Extraneous ^{40}Ar includes any ^{40}Ar in a mineral other than the radiogenic component which accumulated after the crystallization of the mineral. Several components of extraneous ^{40}Ar are recognized by Damon. They are: transient ^{40}Ar, inherited ^{40}Ar, nucleogenic ^{40}Ar, enviromental excess ^{40}Ar, atmospheric ^{40}Ar contamination, xenolithic ^{40}Ar, and radiogenic ^{40}Ar contamination. The concepts of transient and inherited argon are not relevant to a discussion of K-Ar relationships in small igneous bodies (which become closed systems by crystallization and cooling, soon after emplacement). Nucleogenic argon is a result of particle reactions. The environmental excess ^{40}Ar component is produced by an external

^{40}Ar partial pressure (other than the earth's atmosphere) and is dissolved in a mineral or rock upon crystallization (Damon, 1970). In the absence of nucleogenic argon, this term is equivalent to the more commonly used term, excess ^{40}Ar (Dalrymple and Lanphere, 1969). The atmospheric argon contamination has already been discussed. Xenolithic ^{40}Ar is introduced into a rock by the incorporation of xenoliths and xenocrysts. The radiogenic contamination is a result of contamination of a sample with foreign solid material in the field or the laboratory. Dalrymple et al. (1975) have shown that some dolerite dike systems contain components of extraneous ^{40}Ar (other than atmospheric). The environmental excess ^{40}Ar component (generally called simply "extraneous argon" by Dalrymple et al., 1975) is probably the most significant extraneous ^{40}Ar component, other than atmospheric argon, for the basalt systems.

The presence of extraneous ^{40}Ar (other than atmospheric) in some dolerite systems suggests that the ideal K-Ar geochronometer is not generally valid for these rocks and therefore a real K-Ar clock must be established to take into account all the components of ^{40}Ar which may be present in actual dolerite samples. The real K-Ar clock must be viewed as an open system, initially, in the presence of an ambient partial pressure of argon which does not generally have the isotopic composition of atmospheric argon. Damon (1970) developed a differential equation for a real K-Ar clock and a solution for

^{40}Ar accumulation in a mineral. Unfortunately, the solution is not applicable to situations where the temperature (and hence the diffusion constant for argon) changes or where the environmental ^{40}Ar pressure changes during the time interval of interest. One might use Damon's equation by assuming abrupt changes in environmental parameters and by using analytical data from different minerals in a rock system, but it would generally be necessary to have data on the relative solubilities and diffusion rates of argon in the different minerals under the different sets of conditions. The necessary data are not available at this time. Thus at the present, even though the presence of extraneous ^{40}Ar can be detected, a mathematical treatment to resolve the actual time of crystallization of a rock system under a significant environmental ^{40}Ar pressure (other than atmospheric) cannot yet be applied.

The observation of K-Ar apparent ages which are clearly higher than the possible geologic age of a rock unit is unequivocal evidence that the rock contains too much ^{40}Ar. But there are also several experimental approaches to the detection of extraneous argon which are independent of any prior knowledge of the age of the rocks involved.

If there is no extraneous argon (other than atmospheric) in a rock, then different samples from the rock should produce the same apparent age (within experimental error), provided, of course, that none of the samples has suffered significant argon loss. The different samples may be either

different whole rock samples from different locations within a rock unit, or different minerals separated from a single rock specimen. Concordance in apparent ages (i.e., agreement within experimental error) is normally accepted as evidence for the absence of extraneous argon (other than atmospheric) as well as for the absence of any significant argon loss (although fortuitous concordance could be observed in a system which has not met these conditions). Conversely, a lack of concordance (discordance) in apparent ages is indicative of problems with extraneous argon (other than atmospheric), or argon loss, or both. A great deal of information about the reliability of different minerals and rocks, with respect to argon loss, is available in the literature. Using this information, discordance due to extraneous argon can be reasonably identified.

The presence of non-atmospheric ^{40}Ar in a non-potassic mineral phase is the most powerful indicator of the presence of environmental excess ^{40}Ar. Quartz from the country rock in contact with a dike can be used for this purpose.

Incremental release of argon from a rock sample by heating at sucessively higher temperatures can produce further evidence of the presence of extraneous ^{40}Ar (other than atmospheric). $^{40}Ar/^{39}Ar$ incremental release spectra are particularly useful for this purpose, but anomalous release of non-atmospheric ^{40}Ar at low temperature (See Chapter III) appears also to be a useful indicator of environmental excess ^{40}Ar in dolerites.

Potassium-argon isochron plots provide a method of analysis of K-Ar data which may be used in two different ways. In the simplest sense, an isochron plot (in which the abundance of the daughter nuclide is plotted versus the abundance of the parent) is a graphical method for illustration of concordance, or the lack of it, among a set of samples which are from the same environment and known to be coeval (or at least to have been accumulating radiogenic ^{40}Ar over the same interval of time). But in addition, isochron plots can possibly be used to identify the amounts of extraneous argon in samples even when the extraneous argon is not entirely atmospheric, and thus to obtain the age of a set of samples which have discordant conventional apparent ages. If different whole rock samples or mineral separates from the same rock plot on an isochron (straight line), then the slope of the line is a function of the age of the rock, unless the agreement of the points to a straight line is fortuitous. Isochron plots can be used with conventional K-Ar data or with $^{40}Ar/^{39}Ar$ incremental release spectra.

Interpretation of Anomalously High Apparent Ages

It has been pointed out (See Chapter III) that many of the samples in this study have K-Ar apparent ages higher than the maximum possible age based on geologic criteria. The only reasonable interpretation of this relationship is that the dikes contain non-atmospheric extraneous argon. The presence

of significant amounts of nucleogenic argon, xenolithic argon, or radiogenic argon contamination may be ruled out, for these samples, leaving environmental excess ^{40}Ar as the only reasonable source of the anomalously high apparent ages.

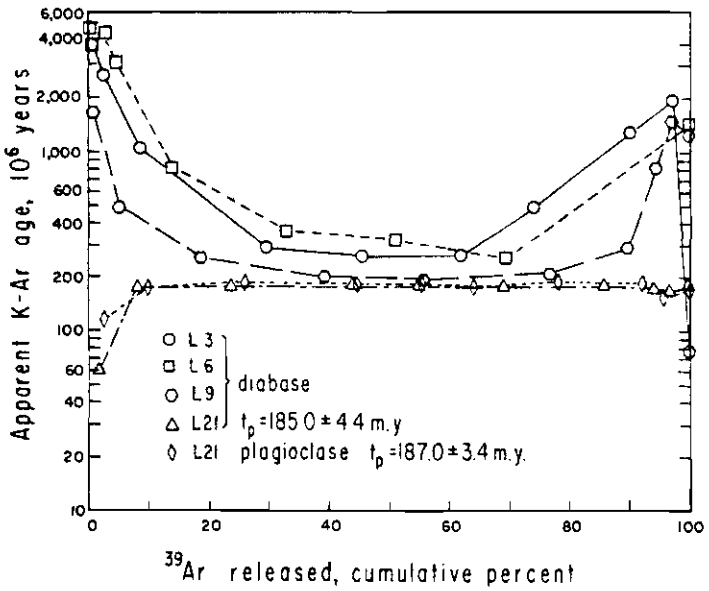
It has also been pointed out (See Chapter I) that the occurrence of apparent K-Ar ages in excess of geologically acceptable dates in Liberian dolerites is likely to be the result of extraneous argon (other than atmospheric) present as an initial argon partial pressure underwhich the dikes crystallized (Dalrymple et al., 1975). These workers used the $^{40}Ar/^{39}Ar$ technique to provide isotopic evidence for the existence of extraneous argon (other than atmospheric) in the dolerite dikes with anomalously old apparent ages.

Irradiation of a rock sample with fast neutrons induces the nuclear reaction ^{39}K (n,p) ^{39}Ar, among many others. Sigurgeirsson (1962) was the first person to suggest that the nuclear reaction was potentially the basis of a new dating technique. Since the amount of ^{39}K in a sample is proportional to the amount of ^{40}K, then the K analysis can be done by the mass spectrometric analysis of ^{39}Ar which is a function of the ^{39}K content. Merrihue and Turner (1966) were the first to apply this method to geologic materials. In the irradiation, other nuclear reactions produce small amounts of argon isotopes. Certain small corrections to the measured amounts of argon isotopes must be applied to obtain a $^{40}Ar/^{39}Ar$ ratio proportional to the $^{40}Ar/^{40}K$ ratio. Details of the corrections and

mathematical calculations of the $^{40}Ar/^{39}Ar$ method can be found in the work of Brereton (1970).

The irradiated rock sample can be fused completely in a single isotopic argon analysis and the apparent age (as in the conventional K-Ar method) calculated. A method which potentially offers more information about the distribution of argon isotopes in the irradiated sample (and thus about the distribution of $^{40}Ar/^{40}K$) is based on incremental release of argon at increasing temperatures. As the argon is released at different temperatures, the isotopic composition of argon released at each temperature can be measured.

A plot of $^{40}Ar/^{39}Ar$ apparent age versus cumulative release of ^{39}Ar produces an "incremental release spectrum". If the sample is homogeneous with respect to potassium-argon ratios, then the same $^{40}Ar/^{39}Ar$ ratio would prevail within each mineral phase, and the same apparent age for each temperature increment would be obtained. This age (under these conditions) can be regarded as valid. If argon was initially present, then the various mineral phases, having differing solubilities for argon, would incorporate argon in different absolute amounts and generally id different proportions to K. Such a condition produces a disturbed incremental release spectrum showing variable apparent ages for different temperature increments (Dalrymple et al., 1975). Figure 21 illustrates this situation for several Liberian dolerite dikes, as well as "undisturbed" $^{40}Ar/^{39}Ar$ spectra for one Liberian dike. The



$^{40}Ar/^{39}Ar$ age spectra of whole-rock diabase and plagioclase from four Liberian sites. Samples L3, L6, and L9 have minima of 268 m.y., 265 m.y., and 203 m.y., respectively, and contain excess ^{40}Ar. Plateau ages (t_p) of L21 diabase and plagioclase probably represent emplacement age. Data for L21 plagioclase are from Dalrymple and Lanphere (1974); data for L3 and L6 are from Lanphere and Dalrymple (1971, samples 8L520 and 8L550).

Figure 21. $^{40}Ar/^{39}Ar$ Incremental Release Spectra for Liberian Dolerites (After Dalrymple et al., 1975).

irregular release patterns are interpreted by Dalrymple et al. to be the result of initial argon (present when crystallization occurred). $^{40}Ar/^{39}Ar$ dating has not been done for the dolerites in this study, but such work is currently in progress at Georgia Tech.

Although no $^{40}Ar/^{39}Ar$ work has been completed for the Georgia samples, there is other evidence in this study which suggests the presence of non-atmospheric ^{40}Ar. Multiple whole rock samples from five dikes in Georgia were analysed. The discordance among the apparent ages of rock specimens collected in each dike is interpreted as being the result of the incorporation of environmental excess ^{40}Ar in the dolerites of Georgia upon crystallization. The discordance found in apparent ages obtained on separated mineral samples is further evidence to support this claim. The discordant results suggest that the various mineral phases, with differing solubilities for argon, incorporated argon in different absolute amounts and generally in different proportions to K.

A convincing way to determine if non-atmospheric argon was present during crystallization of dolerite dikes is to see if a mineral phase such as quartz (which contains no K and therefore should not contain radiogenic argon), in fact does contain such argon. Three quartz samples collected from the country rock in direct contact with the dikes in Rabun County contain non-atmospheric argon. This is regarded as environmental excess ^{40}Ar, since these quartz samples should

contain environmental excess ^{40}Ar and therefore produce invalid K-Ar apparent ages. Further work on quartz samples might enable one to establish how much environmental ^{40}Ar a dike was exposed to and provide the basis for a correction for the environmental excess ^{40}Ar component.

Low Temperature Release of Non-atmospheric Argon

The anomalous release of non-atmospheric ^{40}Ar at low temperatures (100-400°C) was observed in experiments involving certain dolerites from Georgia (See Chapter III). It is suggested that this anomalous release of non-atmospheric argon at low temperatures is a way of screening dolerites which have been affected by environmental excess ^{40}Ar. The definition of environmental excess ^{40}Ar given by Damon (1970) is expanded for this study on the basis of experimental evidence to include the argon which may become ultimately trapped in such a way that it may be released at low temperatures. The argon which is released at low temperatures is interpreted to be argon which was somehow trapped between grain boundaries or which perhaps diffused into intergranular positions after crystallization. This component of non-atmospheric ^{40}Ar is suggested to be part of the environmental excess ^{40}Ar component. Thus, in light of the slight addition to Damon's definition of environmental excess ^{40}Ar, it is proposed that the notation $^{40}Ar_{exc}$ be used for environmental excess ^{40}Ar which is released at low temperatures as well as that which diffuses out of crystals at elevated temperatures along with radiogneic argon.

Isochrons

An isochron diagram is produced by plotting data from a set of coeval samples (whole rock or mineral separates) on a graph for which the independent (X) axis is the amount of radioactive parent and the dependent (Y) axis is the amount of daughter. If the individual samples have all been closed systems, the data may plot on a straight line whose slope is a function of the age of the set of samples.

In the K-Ar method, three type of isochron plots can be constructed. These are the ^{40}Ar-^{40}K isochron diagram, the $^{40}Ar/^{36}Ar$ versus $^{40}K/^{36}Ar$ isochron diagram, and the $^{40}Ar/^{36}Ar$ versus $^{39}Ar/^{36}Ar$ isochron diagram. Shafiqullah and Damon (1974) have discussed the principles of these types of diagrams. Using a series of ten models for contributions to the ^{40}Ar which may be measured in a geologic sample, they discussed the interpretation of data plotted on isochron diagrams and the limitations of such interpretation. Their models ranged from the simplest ^{40}Ar component combinations of radiogenic and atmospheric ^{40}Ar to complex combinations of radiogenic ^{40}Ar, atmospheric argon, environmental excess ^{40}Ar, and diffusional loss of ^{40}Ar.

If extraneous argon is present within a set of coeval samples, a plot of ^{40}Ar (non-atmospheric) versus ^{40}K will yield a valid isochron only if the concentration of extraneous argon is the same in all of the samples (excluding the possibility

of losses of radiogenic argon which are coupled with variations in extraneous argon content in such a way as to fortuitously cause the samples to fit a valid isochron). This is a condition which is not likely to be met, even for whole rock samples taken in close proximity to one another. It is certainly not to be expected that different minerals separated from rock samples will have incorporated the same amount of extraneous argon. Conversely, a scatter of points on the ^{40}Ar versus ^{40}K diagram is a good indicator of the presence of extraneous argon (if argon loss may be ruled out as an important factor).

The ^{40}Ar Versus ^{40}K Isochron Diagram

Four plots were constructed, for the dolerite dikes in Georgia for which three or more different samples were analysed for each dike. Figures 22a and 22b are for the Rabun County dikes. The data do not closely fit a straight line in either case. If the separated mineral samples are excluded, the (whole rock) samples in Figure 22a would not show a great deal of deviation from a straight line with the approximate slope for a 200 m.y. old set of samples, but such a line would have an intercept of the ^{40}Ar axis corresponding to about 10 nl/g of excess argon. The samples from Figure 22b do not come close to any reasonable isochron. The samples from the Stone Mountain dike (Figure 22c) show very little spread in K content. The character of the variation shown is easily interpreted as a variation in the amount of extraneous argon. Figure 22d shows

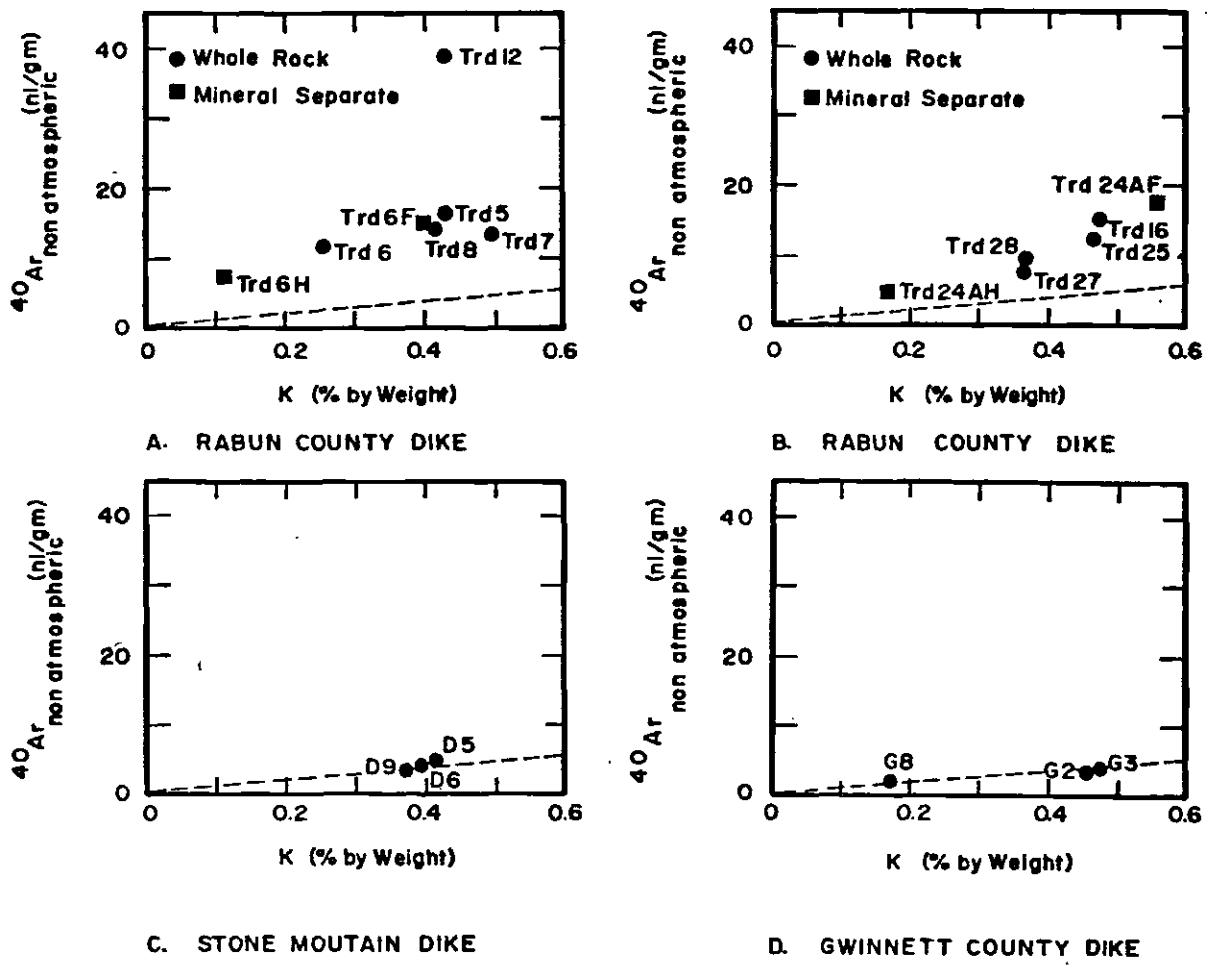
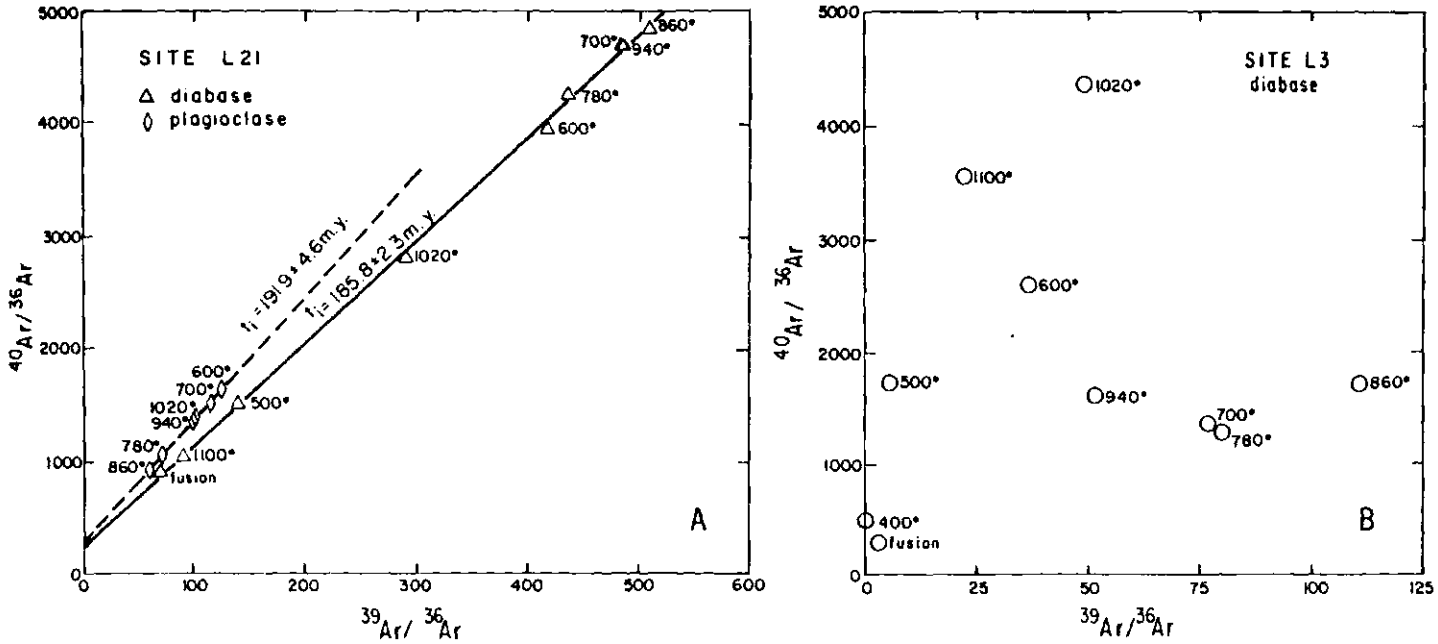


Figure 22. Isochron Plots (^{40}Ar Versus K in weight percent) for Selected Dolerites of Georgia.

data for three samples from a Gwinnett County dike. Although the points appear to fit a straight line, the line has a positive intercept on the ^{40}Ar axis. Such an isochron cannot be considered to be valid unless there is some way of knowing that the concentration of extraneous argon is the same in all samples. In fact, the slope of the line through the Gwinnett County samples corresponds to an unreasonably low age, suggesting that sample G8 has more extraneous argon than the others. It is concluded that each of these dikes incorporated extraneous argon in variable concentration upon crystallization and cooling.

The $^{40}Ar/^{36}Ar$ Versus $^{39}Ar/^{36}Ar$ Isochron

The $^{40}Ar/^{39}Ar$ dating technique was not used in this study. However, Dalrymple et al. (1975)constructed isochron plots of this type for some of the Liberian dolerite dikes which contain extraneous argon and for one dolerite which intrudes the Paynesville sandstone and is thought not to contain extraneous argon. For the latter, the argon released incrementally from a plagioclase sample and a whole rock sample by heating at successively higher temperatures showed $^{40}Ar/^{36}Ar$ and $^{39}Ar/^{36}Ar$ ratios which fit straight lines intersecting the $^{40}Ar/^{36}Ar$ axis at points not significantly different from the atmospheric argon ratio of 295.5 (See Figure 23). Slopes of these lines must represent, with little uncertainty, the age of the rock. For the samples with anomalously old apparent ages, a scatter of points was observed, thus no isochron could



$^{40}Ar/^{36}Ar$ versus $^{39}Ar/^{36}Ar$ isochron diagrams for whole-rock diabase and plagioclase from Liberian sites L21 (A) and L3 (B). Argon isotope ratios have been corrected for K-derived ^{40}Ar and Ca-derived ^{38}Ar and ^{39}Ar. Only plateau points are used for site L21 isochrons; indicated isochron ages (t_i) probably reflect emplacement age. Data for site L3 do not plot on an isochron because sample contains excess ^{40}Ar.

Figure 23. $^{40}Ar/^{36}Ar$ Versus $^{39}Ar/^{36}Ar$ Isochron Plots for Selected Liberian Dolerites (After Dalrymple et al., 1975).

be constructed from the data. This is a clear indication of variable amounts of extraneous ^{40}Ar in these samples.

The Relationship of Environmental Excess ^{40}Ar to Country Rocks

The dolerites in Georgia intrude metamorphic rocks which were at one time covered by sediments in the Appalachian Mountains. The age produced by K-Ar dating of micas in the Piedmont (Smith et al., 1969) range from about 320 to 240 m.y., for that portion of the Piedmont where dikes are found. These dates presumably indicate cooling ages when the roots of the mountain system cooled low enough for minerals to retain radiogenic argon. The metamorphism produced a variety of metamorphic rocks which are at least Paleozoic in age. These rocks are similar to the metasedimentary and metaigneous rocks of Liberia. It is suggested that the extraneous argon (other than atmospheric) is derived by heating of the rocks which the dolerite dikes intrude and that the amount of extraneous argon incorporated is related to the type of rock intruded.

Figure 24 shows metamorphic isograds of Georgia with corresponding radiometric dates (Smith et al., 1969). The line which separates samples with anomalously old ages from acceptable ages (Figure 18) approximates one of the metamorphic isograds in Figure 24 (the line separating kyanite and sillimanite grade rocks which runs through Atlanta). Most of the dikes which gave K-Ar apparent ages within acceptable age limits intrude rocks of sillimanite grade. The dikes in the

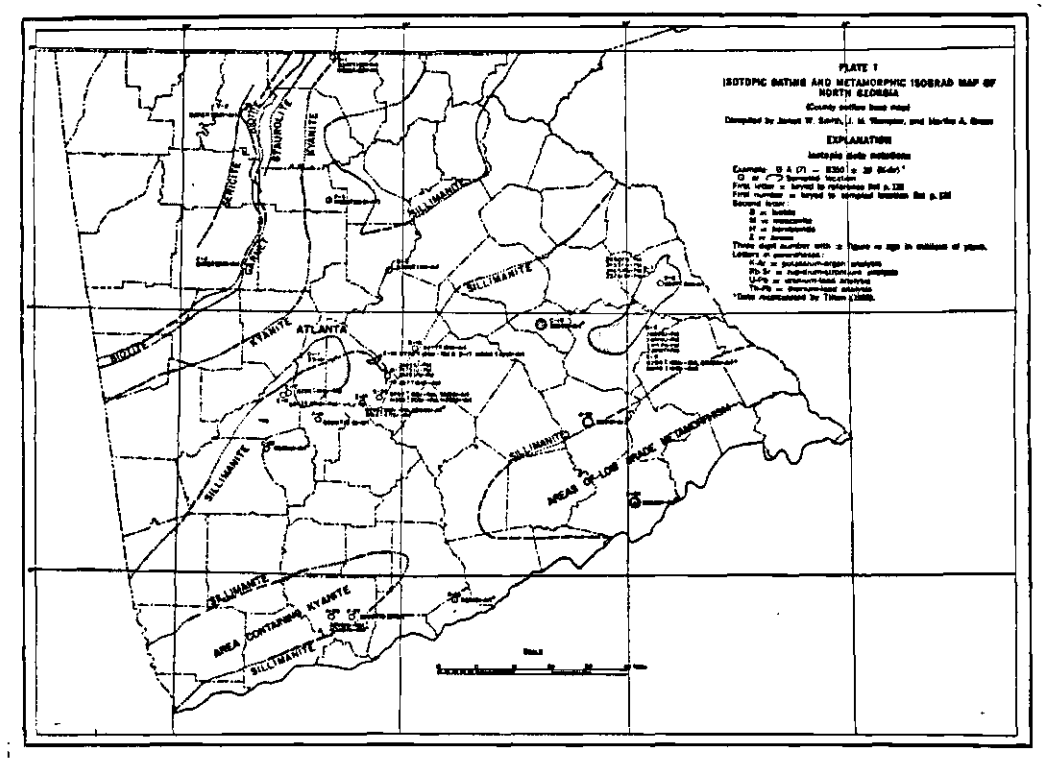


Figure 24. Metamorphic Isograd Map of Georgia with Radiometric Dates (After Smith et al., 1969).

Kyanite grade rocks appear to be contaminated with $^{40}Ar_{exc}$. The dike in Meriwether County was sampled in the sillimanite zone and the dike samples in Talbot County were collected from kyanite grade rocks. The two dikes are very similar in their chemical composition (both are high-Ti-high Fe_2O_3 quartz tholeiites), which suggests that they may have been derived from the same magma, yet the difference between their apparent ages is about 35 m.y. (190 m.y. and 225 m.y. respectively). If these dikes were formed from the same magma, the difference in apparent ages may be reasonably explained if environmental excess argon is present in greater amounts for the Talbot County dike. (Another interpretation would be that the younger date is a result of diffusional loss of radiogenic argon.)

The Argon Loss Problem

Armstrong and Besancon (1970) have suggested that a low grade burial metamorphism was responsible for the presence of zeolites found in dolerites from Pennsylvania, New Jersey, Vermont, and Connecticut. Weigand and Ragland (1970) noted the occurrence of pumpellyite and prehnite in dolerites from North Carolina and South Carolina. The presence of secondary mineralization owing to metasomatism or weathering indicates that a rock has not been a closed system with respect to argon and potassium. This would be significant only if the time of secondary mineralization was distinctly later than the time of crystallization of the rock, and if the mineralization involved K bearing phases.

The presence of secondary mineralization was noted for the Georgia dolerites. None of these minerals indicate such a low rank metamorphism. No zeolites were found in the Georgia dolerites analysed in this study. Serpentine was an alteration product of olivine. Pyroxene alters generally to biotite which subsequently alters to chlorite. Plagioclase has been sausseritized (which is a late stage hydrothermal alteration of plagioclase). These alterations appear to have occurred during the crystallization and cooling of the rock and should not have significantly disturbed the argon geochronometer.

The presence of solid state transformations enhance diffusion of radiogenic argon. Micropegmatite has been cited as a material susceptable to the loss of argon, because of perthitization of K feldspar. Also, twinning and development of 001 and 100 lamellae in pyroxenes might enhance the rate of radiogenic argon diffusion (although pyroxene has very little radiogenic argon present to begin with). The quartz normative tholeiites tend to occur more abundantly in lower age groupings than do olivine tholeiites. This relationship may be a result of the presence of micropegmatite which may cause the quartz normative samples to suffer from diffusional loss of radiogenic argon.

Laboratory Induced Loss of ^{40}Ar

Another way to lose argon is to induce its loss in the laboratory inadvertently. Prebaking samples which contain

environmental excess ^{40}Ar causes the loss of some of the loosely bound environmental excess ^{40}Ar component, so a true measurement of the total amount of ^{40}Ar cannot be made.

Relationship of K-Ar Apparent Ages to the Ages of the Dolerites of Georgia

Geologic Constraints

The geologic constraints on the timing of continental rifting have already been developed from previous research in Chapter I. They will be quickly reviewed. An absolute upper limit for the age of the dolerites is 290 m.y. It is felt that none of the dikes are probably older than 230 m.y., but the evidence is not as convincing as the absolute upper limit. The compressive forces which formed the Appalachians must have subsided by the time the continents began to rift in a tensional upwarping of continental crust. On the basis of a modern interpretation of the continental rifting process the minimum age of intrusion of dikes would be given by the oldest sediments in the Atlantic Ocean. Paleomagnetic geochronology suggests that the Keathley Sequence is approximately 151 m.y. old. Thus, the age which is accepted as a possible lower limit for the intrusion of the dikes is 151 m.y. in southeastern United States. An absolute minimum age is given by the Cretaceous overlap of the dikes in the Coastal Plain of Georgia and Alabama. The time interval of 160 to 230 m.y. is taken as a reasonable estimate for the duration of magmatic activity and formation of rift zones which separated Laurasia

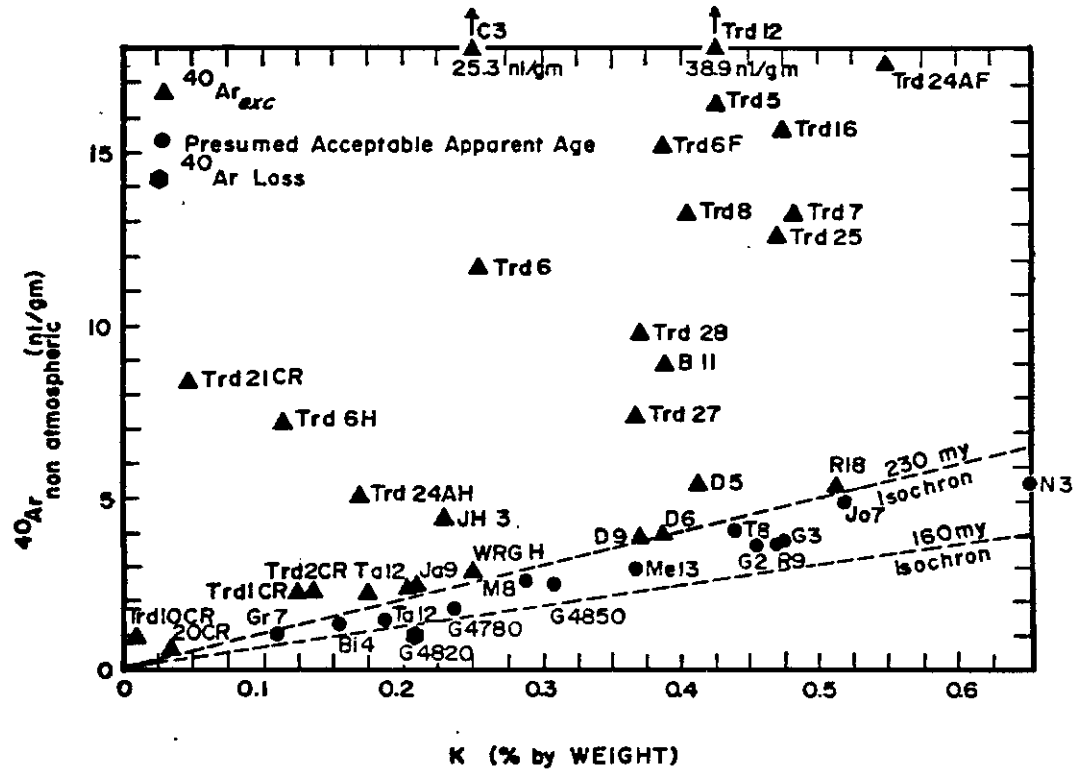


Figure 25. Plot of ^{40}Ar Versus K (in weight Percent) for Georgia Dolerites Dated in this Study (with two Reference Isochrons).

from Gondwanaland. This 70 m.y. age range fits current ideas on how long continental rifting might require.

Figure 25 is a plot of apparent radiogenic argon versus potassium. The estimated limits of 230 m.y. and 160 m.y. were used to produce two reference isochrons in the diagram. Samples which fall between the reference isochrons have apparent ages which are geologically reasonable. Samples which fall above the wedge shape produced by the two reference isochrons are those which have definitely been influenced by an initial ^{40}Ar partial pressure ($^{40}Ar_{\underline{exc}}$ incorporated upon crystallization).

Nine of the points which fall between the reference isochrons are based on duplicate analyses of samples collected from the contact margins of one dike from each of nine counties. Petrographic examination of most of these samples has revealed no significant alteration. In the absence of clear evidence of excess argon in these samples, the K-Ar apparent ages may be provisionally accepted as a reasonable approximation to the crystallization ages of these rocks. But the possibility that these rocks contain small amounts of environmental excess ^{40}Ar is clearly present, so further whole rock samples and mineral separates must be analysed to establish whether the dates for these dikes are in fact valid. Thus, the validity of K-Ar apparent ages obtained from some of the dikes can only be provisionally accepted until further research

has been accomplished. The overwhelming case for $^{40}Ar_{\underline{exc}}$ in most of the dikes in Georgia indicates that many of these dates may not be valid and cannot be used in an interpretive way concerning the sequence of events which occurred during rifting of Laurasia from Gondwanaland.

CHAPTER V

GEOLOGIC AND TECTONIC DISCUSSION WITH RESPECT TO K-Ar GEOCHRONOLOGY

The Formation of An Old Triple Junction

The formation of triple junctions (or three-armed rifts) has already been suggested to be the surficial expression of convection cells centered about convective hot spots or mantle plumes. Triple junctions of various types have been observed. A triple junction which consists of three spreading ridges is the stable type (The Afar triple junction is the stable sort). It has been inferred that most of the triple junctions formed in the rifting of Pangaea are of the stable sort (Dietz and Holden, 1970). It has also been suggested that the tensional forces which produce fractures which are intruded by basaltic magma are also associated with the formation of triple junctions of the stable sort, with three spreading ridges intersecting. The Afar Region in eastern Africa is a good example of the present day formation of a triple junction of the stable type. In this study, we are looking at two or more ancient spreading centers which have long ago been activated and the rifted continents subsequently dispersed.

The convective rise of a plume has been suggested as the mechanism which forms triple junctions (Dewey, 1972). By looking at the present day distribution of hot spots, especially with respect to triple junctions presently forming, one

might be able to make inferences concerning the development of ancient spreading centers whose record has been largely obscured by subsequent geologic events.

Burke and Wilson (1976) have mapped over 100 hot spots presently under the earth's crust. They have observed that hot spots may be located at the centers of an upwelling convection cell or may cut indiscriminantly across convective currents. Hot spot activity under the African continent is much greater than for those plates which seem to be moving fairly rapidly (approximately 2 cm/yr or greater), such as the North and South American plates. The African plate seems to be growing on almost all fromts (except the northern edge, which is a subduction zone) and has been shown to be in the approximate same location for the last 30 m.y. and possibly longer. Since continental rifting and separation are presently occurring in the Afar Region of Africa, an analogous situation can be considered for the separation of North America from Pangaea.

The Afar Triple Junction

Sequence of Events in the Afar Region. In the Afar Region, rifting is presently occurring as a result of a developing triple junction with two activated arms and one arm whose separation is not yet complete (the Ethopian Rift). The Red Sea and Gulf of Aden are the two initially active rift arms with the megashear in the Gulf of Aden developing first.

Two active areas of updoming in the Afar Region can be presently observed, the highlands bordering the Red Sea, and the Ethopian Rift zone. In the Red Sea, sea-floor spreading has just begun; this was the second arm in the triple junction to activate (Gass, 1972). Gass showed that in the rift zones of the Afar Region, attenuation and normal faulting of the crust was first associated with alkali vulcanism, then a period of quiesence, then a second transition peralkali magmatic intrusive event, followed by a second period of quiesence, and finally a third magmatic event which involved the intrusion of tholeiites. It is considered that after this point in the development of tectonic events that rifting has ended and that continental drift and sea-floor spreading are well underway for a particular rift arm. Vertical uplift and attenuation were suggested by Gass (1972) to be continuous, but vulcanism seemed to occur episodically, but not periodically. Gass suggested that the African rifts were the result of a number of lithothermal systems producing separate areas of updoming.

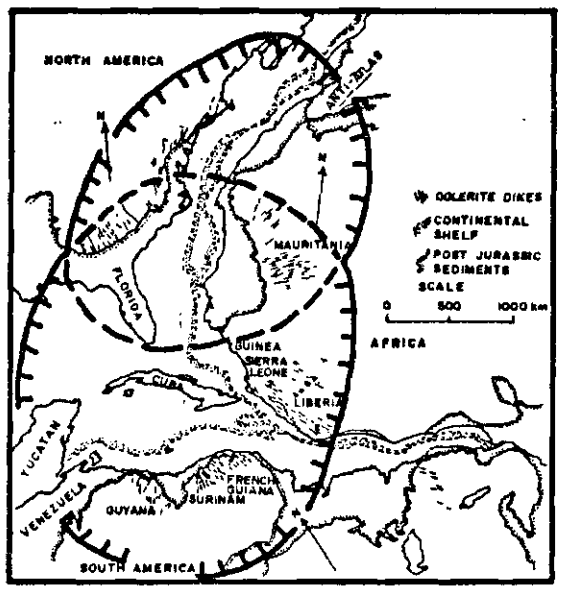
Burke and Wilson (1976) imply, in their diagram which represents the population of hot spots on the surface of the earth, that the updoming in the Red Sea and Ethopian Rift are the result of several hot spots in each arm. The hot spots group in two areas of updoming, with several hot spots under each dome.

Analogy of an Ancient Triple Junction to the Afar Region

The cumulative updoming around two distinct centers

might be responsible for the more or less elliptical distribution of dikes observed in May's reconstruction (1971). Figure 26 shows diagrammatically two proposed areas of updoming drawn in over May's reconstruction. It is proposed that a tectonic regime might have existed in Pangaea similar to that of the present day Afar Region. The stage of development shown in Figure 26 for the triple junction near Georgia (there were several triple junctions responsible for the breakup of Pangaea) was where two rift zones (or spreading centers) had activated between North America and Africa, and between North America and South America. A triple junction (in the strictest sense) would not have existed in the early stages of continental rifting of Pangaea and thus it would probably be more precise to call the two activated arms of a forming triple junction, simply rift arms or spreading centers.

Duration of Magmatic Activity in Continental Rocks During the Formation of a Triple Junction. The Afar triple junction has been magmatically active in the form of discrete episodes for the last 50 m.y., and the chemistry of the magmas and style of deformation has changed during that time. Deformation begins with an initial stage of tensional updoming and ends with a final compressive stage associated with diapiric structures rising in the newly rifted margins and newly formed ocean floor (Schneider, Vogt, and Lowrie, 1969). Pautot, Auzende, and Le Pichon (1970) showed the existence of a deep



OCCURRENCE OF DOLERITE DIKES IN A PRE-RIFT RECONSTRUCTION OF NORTH AMERICA, SOUTH AMERICA & AFRICA

Figure 26. Reconstruction of North America, South America and Africa in their Pre-Rift Positions (After May, 1971) with Two Proposed Areas of Updoming.

sea salt layer, similar to the one forming in the Red Sea today, along the North Atlantic margins and suggested that the salt layer formation is related to the end phase of continental rifting in successive arms of a triple junction which split North America, South America and Africa. Thus the compressive tectonic regime under which diapiric rise of salt domes occurred indicated the end of tensional forces which were associated with continental rifting in a particular rift arm. It has already been noted that the available K-Ar data on dolerite dikes from North America, South America, and Africa suggest a range in age from 160 to 230 m.y., an interval of 70 m.y., which is greater than the duration of magmatic activity in the Afar Region. Activity is still present in the Afar Region today. It is suggested that the supercontinent, Pangaea, became tectonically fixed for at least 30 m.y. or longer which led to an increased number of hot spots underneath the stable continental crust. The effects were reflected in the surficial geology as updoming and in continental rifting along three-armed rifts centered at convective mantle plumes.

Mantle Plumes, Chemical Plumes, and Hot Spots

The distribution pattern of dikes in the continents reconstructed to a pre-rift position suggests a maximum limit on the size of a mantle plume which rifted North America from Pangaea. The extent of the dikes produces a more or less elliptical pattern which has its long axis oriented in an approximate north-south direction and is 3400 km in length and 1700 km

in width. Burke and Wilson (1976) have suggested that the size of most hot spots is up to 200 km in diameter. If the hot spots are this small then it would seem that several hot spots would be required to cause updoming over as large an area as the emplacement of the dikes suggest. It is suggested that the triple junction where continents initially began rifting could be the result of the detachment of a peridotitic mushroomed shaped crystal mush (originating in the asthenosphere or deeper, in the case of a chemical plume) at least 20-200 km in diameter separating from the more dense hypothetical rock, pyrolite, of the upper mantle (below the asthenosphere) and rising upward in a convection cell center about the mantle plume (Green and Ringwood, 1967). The mantle plume has also been referred to as a hot spot. Anderson (1975) suggests that some mantle plumes may be chemical plumes located deep in the mantle (or possibly upper core).

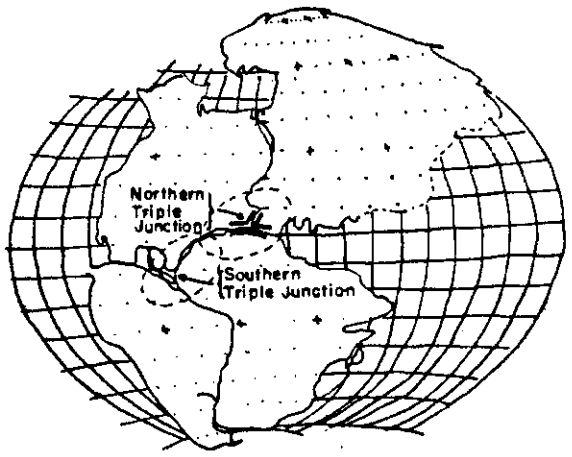
Models of Hot Spots. A distinction might be made between hot spots which are centered in an upwelling convection current and those which cut across convection currents. It is suggested that the former would tend to be larger and more mushroomed shaped than the latter and that the former were probably the locations of triple junctions responsible for the rifting of North America from Pangaea. It can be observed that not all hot spots are located underneath triple junctions, and it might be that only the larger plumes cause triple junctions. The larger plumes may be located in the

rift arms of at least two triple junctions, the northern and souther ones (Figure 26). The northern triple junction was located near New England and Nova Scotia and the southern triple junction was located near Georgia, Surinam, and Liberia (in a reconstructed model of Pangaea).

Interpretive Reconstruction of Events in Continental Breakup

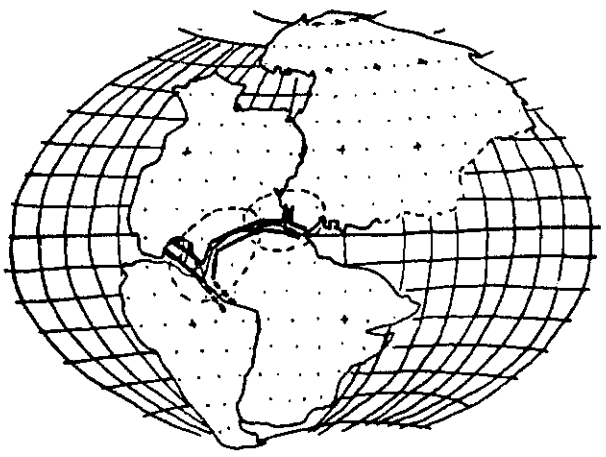
Ancient triple junctions (then, rift arms or spreading centers) can be envisioned in a reconstructed model of Pangaea to have been responsible for the breakup of the continental area which now comprises North America, South America, and Africa. In fact, rift zones (part of later-formed triple junctions) forming at similar times were suggested to have been responsible for the breakup of Pangaea (Burke and Dewey, 1973). It is suggested in the present study that the rift zones were part of at least two triple junctions which rifted Laurasia from Gondwanaland. The rift zones appear to have activated from the north to the south. Figure 27 diagrammatically shows the two triple junctions and a proposed sequence of events.

The northern most triple junction is suggested to have activated around 225-230 m.y. ago with a maximum amount of igneous activity at 200 m.y. ago. The northern triple junction developed much slower, subsequent to its activation than the southern one. The dikes associated with the southern triple junction which was near Georgia (in Early Jurassic) have been dated with paleomagnetism and K-Ar whole rock and mineral



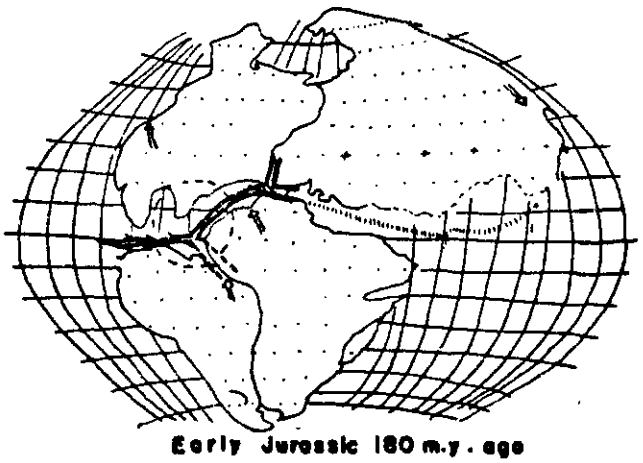
Partial Reconstruction of the Continents
End of the Permian
225 m.y. ago

By the end of the Permian, Domal Upwarping and the activation of two spreading centers in the northern triple junction (and associated magmatic activity) occurred. Upwarping of the crust in the southern triple junction began (but the spreading centers here had not developed by this time).



Late Triassic 200 m.y. ago

At the height of magmatism in the northern triple junction, Graben formation occurred during Middle Triassic time. At the southern triple junction two spreading centers had developed, between North America and South America, and between North America and Africa. The rift Arm between Africa and South America did not develop until Cretaceous time and is dotted to show this inactivity.



Early Jurassic 180 m.y. ago

By Early Jurassic time, igneous activity had subsided in the northern triple junction (and did not reactivate until Tertiary times). In the southern triple junction magmatic activity peaked and probably did not end until approximately 160 m.y. ago.

Figure 27. Proposed Sequence of Events in the Breakup of Pangaea (on a base map of Dietz and Holden, 1970, exclusive of India, Australia, and Antartica).

analyses. Watts (1975) suggests that the dikes in Georgia were intruded approximately 170 m.y. ago, on the basis of paleomagnetic data. The youngest date produced in the study for a dolerite dike was 186 ± 4 m.y. The K-Ar study of Liberian dolerite dikes by Dalrymple et al. (1975) suggests a 170-190 m.y. emplacement of the dikes associated with the southern triple junction. Neathery et al. (1975) produced a 161 m.y. date on a quartz tholeiite dike in Alabama. The fact that Schmitt (1975) revised the date of the lower Keathley Sequence next to South Carolina in the Atlantic Ocean to 151 m.y. with paleomagnetic data further supports that the southern triple junction could have possibly activated and had its most active magmatic phase later than the northern triple junction.

Activation of the Arms of an Ancient Triple Junction

The southern triple junction which was involved in the separation of North America from Pangaea is suggested to be of the stable sort with three spreading ridges intersecting. One of the spreading ridges was subsequently offset by transform faults and became a megashear. This can be seen in Figure 27. The southern triple junction became magmatically active when rift zones developed, forming a spreading ridge and megashear between Southern North America and Northern South America (southern triple junction). The rifting and magmatic activity occurred slightly later in the southern triple junction than in the northern triple junction although

rifting and sea-floor spreading in the south proceeded at at a much greater rate. Shortly after rift zones in the northern triple junction developed, the rift arm which began the separation of North America from Africa developed as a spreading ridge. The arm which separated South America from Africa was not activated in the developing triple junction during the initial rift stages of North America from Pangaea. The third arm of the southern triple junction did not activate as a rift zone until much later in time (approximately Cretaceous).

Implications on Continental Rifting from Presumed Valid K-Ar Ages of the Georgia Dolerite Dikes

Timing of Continental Rifting in Georgia

It has been suggested already that possibly the activation of the southern triple junction (and rift zones) which was associated with the dikes in Georgia occurred about 170 m.y. ago. This is distinctly later than the ages of the dikes and sills in northeastern North America and may suggest that hot spots activated later in the south. It is also possible that vulcanism at the southern and northern triple junctions was episodic but not periodic and lasted over about a 70 m.y. time span with at least three magmatic surges and intervening periods of quiesence at each triple junction but not necessarily at the same time. Sander's geologic evidence supports three magmatic surges, and Smith et al. (1975) observed that three chemically distinct types of intrusions represent three magmatic events. Three distinct periods of time

can be seen in the provisional K-Ar apparent ages listed in Table 6. Accepting the ages provisionally allows the following interpretation. A magmatic intrusive event occurred at 225 m.y. ago in Georgia intruding tholeiitic magma into fractures which were open at that time. Accepting the provisional dates also suggests that quartz normative and olivine normative tholeiites intruded in the initial magmatic event in Georgia. A period of quiesence of approximately 10 m.y. or so occurred before a second magmatic event occurred by 200 m.y. ago with the intrusion of quartz normative and olivine normative tholeiites. A second period of quiesence of 10 to 15 m.y. occurred followed by a final magmatic heave and subsequent intrusion of quartz and olivine normative tholeiites again. The last magmatic event occurred by 180 m.y. ago in Georgia. The 161 m.y. age for dolerites in Alabama suggests that possibly a fourth period of magmatic activity occurred in the southeastern United States. This is one of the possible interpretations which can be made with the K-Ar data, but it can only be provisional in nature. Table 6 involves a small number of samples and the three patterns might overlap with a larger number of analyses.

The overwhelming problem with environmental excess ^{40}Ar in the dolerites of Georgia suggests that possibly none of the dates are valid and all samples contain varying amounts of $^{40}Ar_{\underline{exc}}$ contamination. If the dates are all too high then the triple junction which was near Georgia may not have activated

Table 6. Dolerite Dikes With Acceptable K-Ar Apparent Ages

Sample	K-Ar Apparent Age* (m.y.)	Comments
Ja9-1C	228± 5	Single analysis Sample contains 5% serpentine
R9-1C	190± 4 (average)	Quartz Tholeiite duplicate analyses 12% Sausserite and 1% serpentine
N3-1C	191± 4	Single analysis 15% Sausserite
Jo7-1C	188± 4	Single analysis 8% alteration products
G3-1C	204± 4	Sample G2 gave an age of 185± 4 m.y. Single analysis, 6% alteration products
Ta12-1C	188± 4 (average)	Triplicate analyses fresh rock sample
T8-1C	221± 5 (average)	Duplicate analyses 6% alteration products
Me13-1C	189± 4 (average)	Duplicate analyses May contain excess ^{40}Ar Fresh rock sample
Bi4-1C	202± 8 (average)	Duplicate analyses 6% serpentine

*The K-Ar apparent ages here are calculated on the basis of old constants given in column a in Table 3.

until as late as 170 m.y. ago and only in one or two periods of intrusion. The paleomagnetic data of Watts (1975) suggest contemporaneous emplacement for most of the dolerite dikes in Georgia.

Systematic Variation In Age of the Dolerite Dikes of Georgia with Chemistry and Spatial Distribution

Variation with Chemical Composition

Several factors control the variation in chemical composition of the dolerite dikes in Georgia as well as the rest of eastern North America. Three important factors are lateral inhomogenieties in the upper mantle (and possible lower mantle), thickness of the crust through which a magma intrudes, and ponding in the lower or upper crust.

Lateral Inhomogenieties in the Mantle. The composition of any dolerite dike will largely depend on the composition of the magma (which originated in the upper mantle),the temperature, and pressure under which the rock formed. The composition of this liquid will be controlled by the particular part of the upper mantle which is partially melted. Figure 5 in Chapter I gives the total range in chemical composition for basalts. It can be seen that there is only a small range in composition which centers in the middle of the Di-Fo-Ne-Q tetrahedron. Only slight changes in the original composition of the liquid will cause the subsequently crystallizing magma to differentiate along distinctly different trends.

Therefore, even though mineralogically, there are only small differences between the olivine and quartz tholeiites; the initial composition of a crystallizing magma will determine the final composition of the crystallizing basalt rock. One of the ways that different initial compositions may occur is by magma originating in different parts of the upper mantle. It has already been suggested that hot spots or plumes are part of the overall mechanism of continental rifting, and it is the magma from these plumes which intrudes the tensional fractures associated with rifting. Thus it could be that different parts of a plume may partially melt and produce a slightly different liquid composition. Furthermore different plumes will most likely differ (slightly) in chemical composition.

It has been suggested that several different hot spots were responsible for the breakup of Pangaea. Anderson (1975) suggested that chemical plumes were different in composition from one another especially with regard to rare earth elements and radioactive elements. He envisioned that when large bodies of a condensing proto-stellar nebula accumulated about a center of gravity for what is now planet earth, their chemistry reflected the position of each body with respect to the proto-sun. Therefore the different bodies which accumulated to form the proto-earth had different chemical compositions, especially with respect to the naturally occurring radioactive elements. (Radioactive elements provide the heat to activate convection.) Thus, as chemical plumes were subsequently

activated on earth, the different amounts of radioactive elements (and other chemical species) of one chemical plume relative to another would be reflected in the differing chemistry of each chemical plume. This differing chemistry could produce slightly different compositions for any liquid resulting from partial melting in the asthenosphere.

Thickness of Crust Through which a Magma Intrudes. The activation of a hot spot or chemical plume which is heated by naturally occurring radioactive elements produced crustal updoming due to thermal expansion. Associated with this updoming is the formation of normal faults and grabens which produce an imbricate stacking of slabs of continental crust. As magma is injected into upper portions of the crust the overlying rock can collapse into the space where the magma had been. The result of this normal faulting, graben formation, and expansion produces crustal thinning toward the center of the domal structure. Erosion also plays an important role in crustal thinning because of the increased potential energy imparted by upwarping of the crust.

It is suggested that magma which has short distances of crust to travel through before crystallizing would have a short residence time in the crust as a magma and would therefore assimilate little material from the surrounding country rocks. Progressing further from the center of the updoming, thicker and thicker crust occurs. Thus, any magma which intruded tensional fractures on the flanks of a domal structure

would have several additional kilometers of crust to travel through, increasing the time the magma spent in the crust. The increased residence time would allow the magma more time to assimilate elements from the country rocks. As continental drift began, a particular portion of the crust could move to a distinctly different part of the chemical plume. A slightly differing composition of the liquid may result in this way.

Ponding Magma in the Crust. This idea was presented by Weigand and Ragland (1970) and Smith et al. (1975). Basically, if a magma becomes trapped as magma chambers in the lower or intermediate levels of the crust then slower cooling rates results in increased chances for assimilation of elements from the continental crust, and allows the magma to differentiate to different chemical compositions

In summary, it is suggested that magma can pond in the crust and evolve chemically, but that is not the only way that the chemistry may vary with respect to different periods and places of intrusion. Lateral inhomogenieties and differing thicknesses of crust through which magma intrudes are additional variables which will ultimately effect the chemical composition of an intruding dolerite dike. These variations along with ones produced by variable temperatures and pressures of partial melting will produce different basaltic rocks.

Variation of Chemical Composition with Age

Petrologically, it has been widely accepted that the

parental magmas to quartz tholeiites were olivine tholeiites or liquids which produced olivine tholeiites as the first crystallizing products. Weigand and Ragland (1970) and Smith et al. (1975) show that the quartz normative tholeiitic compositions could be derived from liquids of olivine tholeiitic composition. Hence, the olivine tholeiites would be older than the subsequent quartz normative tholeiites. The derivation of different types of quartz normative tholeiites has already been discussed. Petrologic constraints require that the different quartz normative tholeites must be derived from olivine tholeiite magmas and not from quartz tholeiite magmas. Thus, one quartz tholeiite cannot be derived from another. Smith et al. suggested that sills, flows, and dikes of the same intrusive event would be similar in chemical composition. The relative order of age for different chemical compositions in decreasing age (from Pennsylvania) are: olivine tholeiite, high-Ti quartz tholeiite, and low-Ti quartz normative tholeiites.

It has been noted that Neathery et al. (1975) determined that a quartz normative tholeiite was younger than an olivine normative tholeiite in Alabama, on the basis of K-Ar geochronology. Heat flow calculation of Irvine (1970) suggest that a 2 km thick sill originally at 1100°C intruding into the base of the crust (approximately 500°C) would require 20,000 years to become half crystalline. Any differentiation would be constrained to occur within the time interval of crystallization.

K-Ar geochronology with an analytical precision of about 2% (4 m.y. for a 200 m.y. old rock) could not possibly see age differences among differentiates from the same magmatic event.

It is proposed that the complete differentiation series would probably be achieved during the cooling of any magmatic event but that subsequent magmatic events could in turn produce similar differentiation schemes and produce olivine and quartz normative tholeiites during each distinct magmatic event. Thus, any correlation of chemistry with age made on the basis of K-Ar geochronology with an inherent accuracy of $\pm$ 4 m.y. at 200 m.y. might be fortuitous or might reflect the systematic loss of radiogenic argon for the quartz tholeiites which contain small quantities of micropegmatite. Figure 28 shows that quartz normative tholeiites in Georgia have ages similar to olivine tholeiites which lends support to the idea that complete differentiation occurs for each magmatic surge (accepting the ages in Figure 28 provisionally). The presence of $^{40}Ar_{\underline{exc}}$ in many of the dolerites of Georgia suggests that the whole system may have been similarly affected by variable amounts of $^{40}Ar_{\underline{exc}}$. In view of this and the complex way in which the chemistry can differ, no really convincing arguments can maintain that all quartz normative tholeiites are older than all olivine normative tholeiites. Figure 28 represents a limited amount of data, so interpretations made on the basis

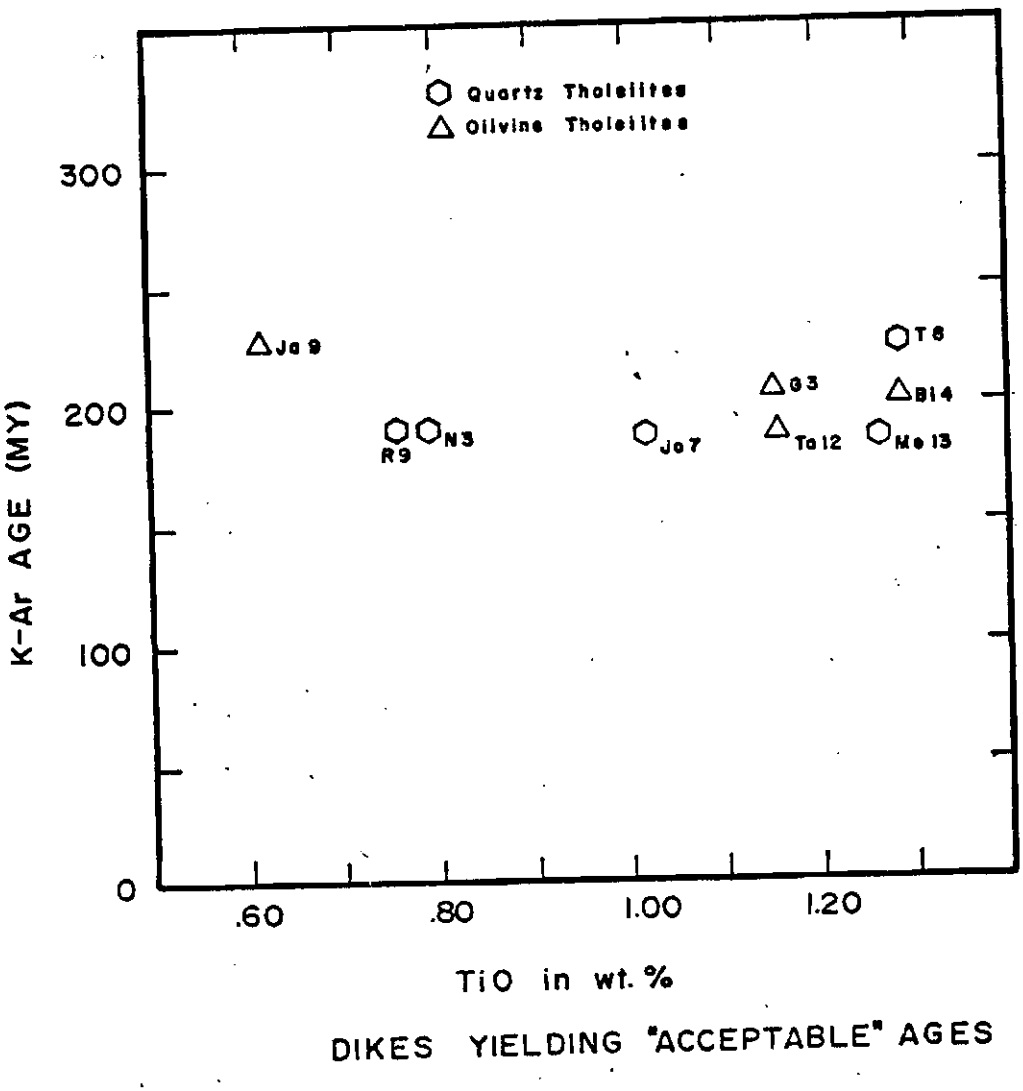


Figure 28. Plot of K-Ar Apparent Age Versus TiO_2 (in weight percent) for Georgia Dolerites with Presumed Acceptable Apparent Ages.

of this figure must be only provisionally accepted and are thus suggested as possible alternative views about age relationships with chemistries of dolerites. If the age groupings in Figure 28 are fortuitous then no real relationship concerning chemical composition with age can be implied. If all the samples suffer from $^{40}Ar_{exc}$ contamination any relationship of chemistry with age would be obscured for the Georgia dolerite dikes.

Systematic Variations in Age and Chemical Composition with Location

Several researchers (Megrue et al., 1972; Smith et al., and Gass, 1970) have suggested spatial relationships with respect to age and/or chemistry, for dolerites intruding areas of continental rifting. Figure 18 (Chapter III) is a map of the dolerites of Georgia with their apparent ages and chemical compositions denoted. The ages above the dotted line represent cases of $^{40}Ar_{exc}$ contamination. The dikes to the south of the dotted line represent the presumed valid age group. The strike of the dikes show no relationship with chemistry or age for the dolerites in Georgia. The absense of an age relationship could result from all the samples being contaminated with $^{40}Ar_{exc}$.

The potassium-argon dates presented in this study must be viewed as preliminary and should be used accordingly. ^{40}Ar (extraneous) in many samples and some samples may have lost radiogenic argon. With the positive knowledge of the existence

of systems which violate the basic assumptions made in the conventional K-Ar geochronological method, the problem can now be approached from a new point of view and the dates should accordingly be viewed as a way to show the geochemical behavior of argon and potassium in a crystallizing tholeiitic magma, and not just a way to determine the timing of geologic events.

CHAPTER VI

CONCLUSIONS

Known geologic relationships place an Early Permian maximum and a Mid-Cretaceous minimum constraint on the geologic age of the dolerite dikes in Georgia. Other geologic considerations indicate that the dolerites of the eastern United States were emplaced during continental rifting and breakup during the Triassic and Jurassic Periods. This is consistent with the range of apparently reliable K-Ar dates on dolerites of the eastern United States, about 160 m.y. to about 230 m.y. This 70 m.y. time interval seems to be reasonable relative to the duration of magmatic activity at the present day center of continental rifting and breakup in the Afar Region, which has been active for 50 m.y.

K-Ar dates on dolerite dikes of Georgia show a very large range in apparent age from 186 m.y. to 1,652 m.y. Many samples have apparent ages much greater than the maximum possible geologic age. The range in ages is similar to the range obtained by Dalrymple et al. (1975) on dolerite dikes in Liberia, West Africa. Multiple whole rock samples from individual dikes, and separated mineral samples, show highly discordant K-Ar relationships, as did most of the samples from Liberian dikes reported by Dalrymple et al.

The results suggest that environmental excess ^{40}Ar occurs in varying amounts within many, but not necessarily all, of the dikes in Georgia. The $^{40}Ar_{exc}$ is dissolved in different amounts in the various mineral phases of the dolerites and is also trapped in small amounts in intergranular positions in dolerite samples. Separated plagioclase contains a higher concentration of extraneous argon than do the ferromagnesian minerals from the same rock, again in agreement with the observations of Dalrymple et al.

Only a small number of Georgia dolerites produced K-Ar apparent ages within the range (160-230 m.y.) which seems reasonable for the emplacement of dolerites in the eastern United States. Since these samples may have small amounts of environmental excess ^{40}Ar, and since some may have suffered loss of radiogenic ^{40}Ar, more thorough study of these dikes will be necessary to establish their ages with certainty. These samples with little, or no, environmental excess argon are generally from the southeastern half of the Georgia Piedmont.

It is suggested that one must view K-Ar dates with a great deal of scrutiny. The time has passed (as other researchers have observed) where geologists can accept an age just on the basis of one K-Ar analysis. Multiple whole rock samples from each dike, mineral separates, and country rock samples should be analysed to establish a consistency of K-Ar relationships, before the age may be accepted as definite. The

$^{40}Ar/^{39}Ar$ method may be used toward this end, with a saving of sample preparation time. The interpretations made from the data presented here must be made provisionally pending further detailed K-Ar studies.

Accepting the data from certain samples (Table 6) provisionally allows a set of models concerning the rifting sequence of continents and the magmatism associated with such tectonic events to be constructed. These models are interpretations, based on provisional K-Ar ages from this study and on the present data available in the literature on K-Ar and paleomagnetic geochronology, heat flow constraints, geochemistry, and geology.

Interpretation

It has been assumed based on geologic constraints in this study that the process of continental rifting and seperation requires a time interval of approximately 70 m.y. Chemical or thermal mantle plumes are suggested to be associated with the development of triple junctions of the stable sort with three spreading ridges intersecting. It is suggested that several small plumes (greater than 20 km in diameter) are responsible for the separation of North America from Pangaea with development of rift zones in at least two triple junctions (and possibly more). A model envisioning several successive magmatic events within continental rocks above newly forming triple junctions can be suggested. A possible sequence of events can be suggested. Each different plume may have activated

at distinctly different times with a small number of magmatic events at each plume but generally within a 70 m.y. time span. On the basis of K-Ar data of this and previous studies, several magmatic events at each plume are tentatively suggested with magmatic surges at slightly different times (within a few million years) for each different plume responsible for rifting North America from Pangaea. At least three periods of magmatic activity occurred at most of the plumes at slightly different times, the first magmatic period occurring about 225-230 m.y. ago, followed by a subsequent period of quiesence, then a second and probably largest magmatic event at approximately 190-200 m.y. ago, followed by a second period of quiesence, and a final magmatic event at about 160-180 m.y. ago which concluded the magmatism associated with the active period of continental rifting (before sea-floor spreading began) in a tensional tectonic regime. These interpretations must only be accepted provisionally, and it should be noted that many other models could be developed on the basis of the available data. The notion of a chemical correlation with time cannot be positively supported or ruled out on the basis of the presently available data on K-Ar geochronology of the dolerite dikes in Georgia.

Recommendations

K-Ar research and paleomagnetic research can be utilized to help further discern the events of continental rifting of Pangaea. It is suggested that the low temperature release of

argon can be effectively used to screen samples for the presence of environmental excess ^{40}Ar. Samples which release large amounts of non-atmospheric argon below 400°C should not be analysed for the purpose of obtaining valid K-Ar ages, but they appear to offer a great deal of information concerning the geochemical and thermal history of the environment into which they were emplaced. Dikes which intrude old metamorphosed roots of pre-existing mountains are prime suspects for containing environmental excess ^{40}Ar. Conditions similar to the one Dalrymple et al. (1975) found in Africa where dolerite dikes intrude relatively young, rock bodies of low K content, or conditions where environmental excess argon may easily escape, are believed to be essential in providing dolerite samples which will yield reliable K-Ar dates.

In any case, analysis of multiple whole rock samples from each dike, taken from across its width and along its strike, and analysis of mineral separates and country rocks in contact with dikes should be considered routine in any K-Ar study if ages are to be established with certainty. The $^{40}Ar/^{39}Ar$ technique can help establish consistency of K-Ar relationships within a sample and should be considered important in future studies involving K-Ar dating of dolerites in Georgia. Petrographic inspection of the actual samples analysed is considered essential to help evaluate whether a system may have undergone loss of radiogenic argon.

Finally, to reconstruct the events of continental rifting, the complete dolerite system of dikes and grabens associated with rifting must be considered. This study analysed only 20 dolerite dikes and one sill underneath the Coastal Plain in Georgia. In Georgia alone, there are many dikes for which no K-Ar, paleomagnetic, or geochemical work has been done. Not until all of the dikes in North America, South America and Africa which were involved in the rifting of North America from Pangaea are considered in a comprehensive research program in K-Ar geochronology, paleomagnetism and geochemistry, will a unified picture of the magmatism associated with this continental rifting emerge.

It is felt that the sills and dikes which intrude Paleozoic and Triassic sedimentary rocks offer a unique geologic situation (in Georgia) in which problems of environmental excess argon should be minimized. Therefore, although many dikes in the Georgia Piedmont are yet to be dated by either K-Ar or paleomagnetic geochronology, emphasis should be placed on dating the sills which intrude the Triassic basins underneath the Coastal Plain of Georgia to obtain valid K-Ar ages.

APPENDIX

This Appendix consists of detailed petrographic descriptions along with descriptions of exact locations of sampling sites. The county in which each dolerite sample was taken will be given along with the latitude and longitude of the sample locality.

Sample B 11 Latitude: $33^{\circ}\ 49'$ Longitude: $84^{\circ}\ 55'$

This sample was collected in Barrow County on Georgia 324 approximately 3 km east of Bethlehem. The dike is classed as a porphyritic, phaneritic, subophitic, olivine tholeiite. It consists of the essential minerals pyroxene, plagioclase and olivine. The olivine crystals occur as large euhedral phenocrysts and are not penetrated by the plagioclase or pyroxene crystals. Smaller olivine crystals occur in contact with plagioclase and pyroxene in the ground mass. The olivine phenocrysts are only in contact with plagioclase. The pyroxene occur interstitially as subhedral augite (diallage) and forms a subophitic texture. The pyroxene crystals are penetrated by the plagioclase crystals. Plagioclase crystals are radially oriented spherulites randomly distributed throughout the rock. Accessory minerals include magnetite and apatite. Euhedral magnetite crystals in contact with all mineral phases are also inclusions. Apatite occurs in minor amounts as inclusions. Secondary mineralization includes some sausseritization of plagiclase and serpentinization of olivine in minor amounts.

Sample Bi 4 Latitude: 32° 48' Longitude: 83° 35'

This sample was collected from a 3 m wide dike located approximately 3 km south of the Macon city limits on Georgia 22C, in Bibb County. The rock is a porphyritic, subophitic, olivine tholeiite with essential minerals, plagioclase, olivine, and pyroxene. The olivine crystals occur as large phenocrysts and optically continuous patches in contact with large phenocrysts of plagioclase. The pyroxene crystals occur interstitially and compose about one fourth of the rock. Smaller plagioclase laths penetrate the pyroxene crystals. Plagioclase crystals occur both as large phenocrysts and as smaller spherulites in the ground mass. The plagioclase sperulites penetrate the pyroxene crystals. Magnetite and apatite occur as inclusions in the large phenocrysts and in the minerals composing the ground mass.

Sample D 9 Latitude: 33° 49' Longitude: 84° 08'

This sample was collected from the aphanitic chill zone of a 12 m wide dike located in Stone Mountain Park, Dekalb County. Petrographically, the rock is an aphanitic, idiomorphic granular, quartz tholeiite. The essential minerals plagioclase and pyroxene are present in approximately equal amounts. The plagioclase crystals are euhedral, equigranular, and occur as spherulites. The spherulites are randomly oriented and do not penetrate the pyroxene crystals. The pyroxene crystals occur as pseudomorphs of plagioclase

and display similar polysynthetic twinning. They occur interstitially to plagioclase and are generally anhedral. Magnetite and ilmenite occur as accessory minerals. The ilmenite crystals can be recognized by characteristic skeletal form. Magnetite and ilmenite replaces both plagioclase and pyroxene. Secondary minerals biotite, chlorite, and serpentine are present in trace amounts.

Sample G 1 Latitude: 33° 55' Longitude: 84° 09'

This sample was collected near the contact of a 15 m wide dike in the aphanitic chill zone. The sample location is approximately 7 km southeast of Lilburn on Riverside Drive which connects to US 78 in Gwinnett County. The rock is an aphanitic, subophitic, olivine tholeiite. Equigranular plagioclase, olivine, and pyroxene crystals compose the essential mineralogy. Olivine occurs as anhedral crystals surrounded by plagioclase crystals. Olivine is interstitial and in contact with plagioclase and pyroxene. Anhedral pyroxene (augite) occurs interstitially to the plagioclase laths and forms the subophitic texture. Polysynthetically twinned, euhedral plagioclase laths occur as radiating spherulites and individual crystals randomly oriented. Skeletal crystals of magnetite occur as the last mineral phase to crystallize and can be seen to be in contact with all the minerals as well as occurring as inclusions. Accessory apatite occurs as inclusions. Chlorite and sausserite can be seen in trace amounts.

Sample G 8 Latitude: 33° 50' Longitude 84° 55'

This sample was collected at the contact of a 10 m wide dike. The dike is located about 4 km north of the city of Lilburn on Georgia 378. The rock is a phaneritic, subophitic, olivine tholeiite. Euhedral to subhedral olivine crystals randomly occur interstitially and are surrounded by plagioclase laths but not penetrated by them. The olivine does not come in contact with pyroxene crystals. Anhedral pyroxene crystals (augite and diallage) occur interstitially and form a subophitic texture with the plagioclase crystals penetrating the pyroxene. Euhedral polysynthetically twinned crystals of plagioclase occur as randomly oriented spherulites and as individual crystals penetrating the pyroxene crystals. Euhedral magnetite crystals occur in contact with all mineral phases and as inclusions. Serpentinization of olivine and sausseritization of plagioclase crystals have occurred to a moderate extent. Traces of chlorite are present.

Sample Gr 7 Latitude: 33° 34' Longitude: 83° 04'

This sample was collected from the center of a 2 m wide dike located approximately 5 km south of Union Point on Georgia 77 in Greene County. The rock is an aphanitic, subophitic, olivine tholeiite. Olivine, pyroxene, and plagioclase occur as essential minerals. The subhedral to anhedral olivine crystals are surrounded by plagioclase crystals and are not penetrated by the plagioclase laths. Smaller olivine crystals

occur interstitially and are in contact with plagioclase and pyroxene crystals. Anhedral pyroxene occurs interstitially to the plagioclase laths and forms subophitic to ophitic textures. Polysynthetically twinned, euhedral plagioclase laths occur as radiating spherulite and as individual crystals randomly oriented throughout the rock. Euhedral magnetite occurs in contact with all minerals and as inclusions in them. Chlorite occurs in trace amounts.

Sample JH 3 Latitude: 34° 11' Longitude: 83° 43'

This sample was collected near the margin of a 17 km dike located on the south side of the city limits of Talmo on US 129 in Jackson County. Petrographically, the rock is a phaneritic, subophitic, olivine tholeiite. The essential minerals olivine, pyroxene and plagioclase are present. Euhedral olivine crystals occur randomly and interstitially. They are surrounded by plagioclase laths but generally not penetrated by the plagioclase. Olivine is in contact with plagioclase only. Anhedral pyroxene crystals occur interstitially and is subophitic. Plagioclase crystals penetrate the pyroxene crystals. Euhedral plagioclase crystals randomly occur as spherulites and as individual laths. Euhedral magnetite occurs in contact with all mineral phases as the last phase to crystallize. Sausserite is present in significant amounts (8%). Some chlorite and biotite occur in trace amounts as alteration products of pyroxene. Serpentinization of olivine occurs in small

amounts. A few patches of kaolinite occur in the thin section.

Sample Ja 9 Latitude: 33° 11' Longitude: 83° 48'

This sample was collected near the contact of a 3 m wide dike located two km west of the Monroe-Jasper county line on Georgia 83 in an abandoned pegmatite quarry in Jasper County. Petrographically, the rock is a phaneritic, subophitic to xenomorphic granular, olivine tholeiite. The essential minerals olivine, plagioclase, and pyroxene are present. Olivine occurs in optically continuous patches as subhedral crystals. Several clusters of olivine crystals occur in the thin section. The olivine is generally in contact with plagioclase although a few crystals are in contact with pyroxene crystals. Anhedral pyroxene occurs interstitially to the plagioclase laths of the ground mass and is penetrated by the laths in many cases. Plagioclase occurs as equigranular crystals of two sizes in the ground mass. The accessory mineral, magnetite, occurs mainly as inclusions in olivine. Some olivine crystals have been serpentinized.

Sample Jo 7 Latitude: 35° 03' Longitude: 33° 28'

This sample was collected in the approximate center of the dike (30 m wide) which is located on a dirt road (near Glawson Cemetary) about three km north of the city of Gray on US 129 in Jones County. Petrographically, the rock is a phaneritic, idiomorphic granular, micropegmatitic quartz tholeiite. The essential minerals plagioclase and pyroxene occur in approximately equal amounts. The euhedral plagioclase occurs

as twinned laths of two distinct sizes. The smaller ones are much more numerous and are about the same size as the pyroxene crystals. Only centers of spherulites are preserved. In general the laths are randomly oriented. Pyroxene occurs as polysynthetic twins which are subparallel to the plagioclase laths and in most cases euhedral. The crystals are not penetrated by plagioclase in most cases. It is obvious that pyroxene replaces plagioclase because pyroxene pseudomorphs are found after plagioclase and in a few crystals one half of a twinned crystal is plagioclase and the other half, pyroxene. The accessory material micropegmatite occurs interstitially and forms triangular intergrowths of K feldspar and quartz. The micropegmatite is generally in contact with plagioclase. Euhedral magnetite crystals occur replacing plagioclase and pyroxene as individual cubid and tetrahedral crystals but in many places grow together to form large patches of magnetite with parts of unreacted plagioclase crystals in their centers. Ilmenite occurs as large skeletal crystals, irregular to dendritic in shape. The secondary minerals sausserite, uralite, and biotite occur in minor amounts.

Sample Me 13 Latitude: $33^{\circ}\ 55'$ Longitude: $84^{\circ}\ 39'$

This sample was collected near the center of a 45 km wide dike located about 5 km north of Greenville on Georgia 362 in Meriwether County. In thin section, the rock is phaneritic, idiomorphic granular, and micropegmatitic. The quartz

tholeiite is composed of the essential minerals pyroxene and plagioclase. The plagioclase crystals occur in randomly oriented laths in patches distributed randomly among patches of pyroxene. Anhedral pyroxene crystals occur in amounts approximately equal to plagioclase and in large patches randomly interspersed among plagioclase patches. The material, micropegmatite, occurs in small amounts interstitially and is triangular in form. Magnetite and ilmenite occur in significant amounts as large patches and are seen to be in contact with plagioclase and pyroxene. They appear to be products of late stage reactions with the melt to give the rock its anomalously high Fe_2O_3 content. Very little weathering products or products of hydrothermal alteration are seen in this rock.

Sample M 8 Latitude: $33^{\circ}\ 55'$ Longitude: $83^{\circ}\ 55'$

This sample was collected from an aphanitic chill zone of a 16 km wide dike located 7 km north of Forsyth, Georgia on Georgia Highway 83 in Monroe County. The rock is a phaneritic, subophitic, olivine tholeiite. Petrographically, olivine, pyroxene, and plagioclase compose the essential mineralogy. Euhedral to subhedral olivine crystals are randomly distributed throughout the thin section. The olivine is not penetrated by the plagioclase or pyroxene crystals. Pyroxene occurs interstitially as randomly oriented crystals which are penetrated b by plagioclase laths. Plagioclase laths occur as large spherulites and are polysynthetically twinned. The accessory

minerals apatite and magnetite occur as mineral inclusions.

Sample N 3 Latitude: 33° 39' Longitude: 83° 44'

This sample was collected from the contact of an 8 km wide dolerite dike found down a dirt road at Mount Zion Church about 5 km northwest of Covington, Georgia in Newton County. The dolerite is a phaneritic, intergranular, rock. Petrographically, the essential mineralogy consists of plagioclase and pyroxene. Euhedral plagioclase laths are randomly oriented with a few large relict plagioclase spherulites present. The laths generally do not penetrate the pyroxene crystals but surround them. The plagioclase and pyroxene crystals are equigranular and the give the rock an equigranular texture. Pyroxene occurs in subhedral crystals randomly oriented in thin section. A few large patches of pyroxene crystals exhibit a subophitic texture. The accessory minerals magnetite, ilmenite, and apatite occur in trace amounts. The plagioclase in this thin section has been extensively sausseritized. No olivine or micropegmatite was observed in thin section. Chlorite and biotite occur as secondary minerals, usually replacing pyroxene, in small amounts.

Sample P 2 Latitude: 33° 25' Longitude: 83° 19'

This sample was taken near the contact of an 8 km wide dike located on a dirt road off of Georgia Highway 44, 7 km northeast of Eatonton, Georgia in Putnam County. The dolerite sample is an aphanitic, porphyritic, subophitic, olivine tholeiite. Petrographically, the essential minerals olivine,

pyroxene and plagioclase occur in the ground mass as phenocrysts. Olivine phenocrysts occur as large euhedral crystals in contact with pyroxene phenocrysts. The pyroxene is poikilophitic, completely surrounding the plagioclase crystals which are slightly larger than those in the ground mass. Pyroxene and olivine occur interstitially between plagioclase crystals in contact with each other. The interstitial pyroxene is subophitic. The plagioclase crystals of the ground mass penetrate the pyroxene crystals. Plagioclase occurs in two sizes. The larger size is the phenocrysts, which are randomly oriented in the phenocrysts of olivine and pyroxene. The smaller size plagioclase crystals of the ground mass are crystallites. The accessory minerals magnetite and apatite occur as mineral inclusions and are in intergranular positions.

Sample R 9 Latitude: $33^{\circ}\ 43'$ Longitude: $83^{\circ}\ 59'$

This sample was collected in the aphanitic chill zone of an 18 km wide dike located near Rockdale Lake about 7 km north of Conyers, Georgia in Rockdale County. This thin section was virtually identical to sample R18 which is from the same dike collected at a different location along its strike in Rockdale County. The detailed petrographic description for both samples will be given under the heading for sample R18. Sample R9 is an aphanitic, microporphyritic, idiomorphic granular, dolerite. It has been sausseritized a great deal but not as intensely as sample R18.

Sample R 18 Latitude: 33°40' Longitude: 83°56'

This sample was collected in the apanitic chill zone of a 17 km wide dike located near Conyers, Georgia approximately 7 km southeast of Conyers on Gees Mill Road in Rockdale County. The dolerite sample is an aphanitic, microporphyritic, idiomorphic granular, quartz tholeiite. Petrographically, the essential minerals plagioclase and pyroxene are present. Euhedral plagioclase crystals occur as microphenocrysts randomly oriented and also as twinned crystallites randomly oriented in the ground mass. The microphenocrysts do not form spherulites as those in the ground mass. The plagioclase crystals have bee considerably sausseritized. Anhedral pyroxene crystals occur as microphenocrysts, some as pseudomorphs after plagioclase. In the ground mass the pyroxene crystallites occur interstitially and are randomly oriented. Generally the pyroxene crystals are not penetrated by plagioclase laths. Micropegmatite occur interstitially in small amounts. The intergrowths of quartz and K feldspar are triangular in shape. The accessory mineral magnetite replaces both plagioclase and pyroxene and is in contact with both mineral phases. Biotite and serpentine occur in trace amounts as secondary alteration of pyroxene.

Sample T 8 Latitude: 32° 44' Longitude: 84° 36'

This sample was collected from the middle of an approximately 60 m wide dike located about 5 km north of the city of Talbotton on Georgia Highway 41 in Talbot County, Georgia. The

rock sample is a phaneritic, micropegmatitic, idiomorphic granular, tholeiite. The essential minerals, pyroxene and plagioclase are present. Pyroxene occurs in patches of equigranular, anhedral crystals with some euhedral pseudomorphs after plagioclase. The patches of pyroxene are randomly distributed throughout the rock. Euhedral plagioclase crystals occur in two distinct sizes. The larger laths are associated with the patches of pyroxene, and the smaller laths occur in the ground mass as patches of radiating spherulites and randomly oriented individual crystallites. The interstices of the small plagioclase crystals are filled with micropegmatite. The accessory minerals magnetite, ilmenite, and apatite occur as mineral inclusions and between grain boundaries. The magnetite and ilmenite replace plagioclase and pyroxene and are in contact with both. Sausseritization of plagioclase is moderate. Chlorite, biotite and uralite occur as secondary alteration products of pyroxene.

Sample Ta 12 Latitude: 33° 34' Longitude: 82° 48'

This dolerite sample was collected from the center of a 10 m wide dike located about 2 km northwest of the city of Sharon, near Kindrick Creek in Taliaferro County, Georgia. The rock is a phaneritic, olivine rich, ophitic to subophitic, olivine tholeiite. Some areas of the thin section look xenomorphic granular in texture. The essential minerals olivine, plagioclase and pyroxene occur in the thin section. Subhedral olivine crystals occur as the largest crystals in the thin section.

The olivine crystals are very fresh. They are surrounded by plagioclase laths and some are penetrated by them. Euhedral plagioclase laths are generally equigranular and form spherulites which penetrate the pyroxene crystals. No sausseritization of the plagioclase is observed. A slight lineation of the plagioclase crystals can be seen, probably due to flowage of cumulate phases in the crystallizing magma. Anhedral pyroxene occurs interstitially as randomly oriented optically continuous patches. The accessory minerals magnetite and apatite can be seen as mineral inclusions and as discrete mineral phases in intergranular positions.

Sample TRD 5 Latitude: 34° $51'$ Longitude: 83° $35'$

This dolerite sample was collected in the aphanitic chill zone of an 8 m wide dike located just north of Moccasin Creek State Park and the Lake Burton Fish Hatchery on Georgia Highway 197 in Rabun County, Georgia. The prefix TRD was chosen early in the development of this study because the dikes were presumed to be Triassic in age, hence the initials TR for Triassinc and D for dike. This practice was not continued for the other samples, because of the age implications and the need to know easily from which county a particular sample came. The dolerite sample is a phaneritic, porphyritic, olivine rich, subophitic, olivine tholeiite. Petrographically, the essential minerals olivine, plagioclase and pyroxene occur. Euhedral olivine crystals occur as large phenocrysts in contact with plagioclase and pyroxene. The large crystals are randomly

distributed throughout the thin section and the plagioclase crystals do not penetrate the olivine crystals in most cases. Euhedral plagioclase laths occur as a few large phenocrysts in contact with the olivine phenocrysts and as smaller laths forming spherulites and randomly oriented individual laths. The accessory minerals magnetite and apatite occur as mineral inclusions. Trace amounts of secondary mineralization can be observed by the presence of chlorite, biotite, and serpentine. Sausseritization of plagioclase occurred in small amounts.
Sample TRD 25 Latitude: 34° $46'$ Longitude: 83° $30'$

This dolerite sample was collected from the center of a dike which is 30 m wide at this location, but pinches and swells in width along its strike. The location of the sample is near Seed Lake (Nacoochee Lake) located in the southwestern corner of Rabun County, Georgia. The dolerite is a phaneritic, olivine rich, ophitic, olivine tholeiite. Petrographically, the essential minerals olivine, plagioclase, and pyroxene are present. Euhedral olivine crystals occur as large optically continuous patches and as large euhedral phenocrysts in contact with plagioclase and pyroxene. The olivine crystals are generally not penetrated by plagioclase although some relict plagioclase crystals are present in the centers of a few olivine crystals. Subhedral pyroxene occurs in large patches, usually ophitic in texture with the plagioclase crystals penetrating the pyroxene. Some of the largest patches of pyroxene crystals completely enclose plagioclase laths producing an ophitic

texture. Euhedral polysynthetically twinned plagioclase laths are randomly oriented and are observed to penetrate some pyroxene crystals as well as being enclosed by some patches of pyroxene. The accessory iron oxide minerals are magnetite, replacing essential mineral phases and ilmenite occurring as skeletal (opaque) crystals. Slight sausseritization and serpentinization has occurred.

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